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The Effects of Warm Mix Asphalt (WMA) Additives on Recycled Asphalt Pavement (RAP)

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Abstract

More than ninety-five percent of the US surface transportation infrastructure system is paved with Hot Mix Asphalt (HMA). Recycling of reclaimed asphalt pavement (RAP) is a critical necessity to save precious aggregates, and reduce the use of costly asphalt binder. The production temperature limits the amount of recycled HMA. Warm Mix Asphalt (WMA) technology provides the option of recycling at a lower than conventional temperature, and hence recycling a higher percentage of RAP, and saving energy and cutting CO_2 emission. The purpose of this experimental study (funded by the Maine Department of Transportation) was to evaluate the effects of WMA additives (SasolWax Sasobit® and Advera® Zeolite) on the rutting, cracking and moisture susceptibility of HMA containing 100% RAP. The following five mixes were prepared and tested for volumetric properties, stiffness and strength: a control mix (RAP with 1.0% PG58-28 virgin binder), two mixes with 1.0% PG58-28 virgin binder plus 2.0% or 4.0% Sasobit® and two mixes with 1.0% PG58-28 virgin binder plus 0.2% or 0.4% zeolite. Contact angle measurements showed no statistically significant difference between the different asphalt binders. Density, dynamic modulus, indirect tensile strength, and contact angle results indicate better performance of recycled HMA with WMA additives compared to conventional recycled HMA.

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Acknowledgements

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Capstone Design Requirement

In accordance with the Accreditation Board of Engineering and Technology (ABET) Accreditation requirements, each Major Qualifying Project (MQP) at Worcester Polytechnic Institute (WPI) must include a description of how the project considered economic, environmental, sustainability, manufacturability, ethical, health and safety, social and political factors. The objective of this project was to evaluate the effect of warm mix asphalt (WMA) additives on moisture susceptibility and bonding of asphalt with aggregate and ABET factors were prominent considerations through the duration of the project.

Manufacturability

Manufacturability is an essential factor in adopting and perfecting a new technology. The design of a warm mix aided recycled asphalt mix is a complicated procedure because it involves combining reclaimed Hot Mix Asphalt (HMA) pavement with the least amount of virgin materials and additives possible while meeting desired performance standards. The challenge arises during the characterization of the Reclaimed Asphalt Pavement (RAP) materials and the development of a design that is economical with satisfactory performance. This significant challenge lies in the obstacle of achieving the required workability of the RAP without compromising the physical properties of the aged binder through high heating temperatures. This predicament can be relieved through the use of WMA additives which lower the viscosity of the aged binder at lower mixing temperatures.

The goal was to produce a standard Maine Department of Transportation (Maine DOT) 50 gyration mix design with approximately 4% air voids with 100% RAP. The amount of virgin asphalt binder must be accurately established to meet the desired 4% air voids. To determine the amount of virgin asphalt binder needed for the mix, the RAP was burnt to find out how much binder was in each grade. Maine DOT specifications assisted in the development of the mix design. Initially, this takes more time than starting with completely virgin materials and using HMA, but over time as the process is perfected, WMA mixes using RAP will be manufactured at an appropriate cost to consumers.

Environmental Issues

Environmental considerations are the basis of this research. WMA and the use of RAP are studied to reduce energy costs and emissions by reducing heating temperatures of the pavement mix. RAP is HMA pavement material that is remixed to make more HMA or WMA pavement. Generally new materials such as virgin binder, aggregate and additives are added to the mix design, but the goal is to produce the most durable pavement with the least amount of new material possible.

In this research, environmental factors were directly addressed by reducing the amount of virgin materials used. The mix design was completely comprised of reclaimed pavement and 1.0% by mass virgin asphalt binder. Varying amounts of PQ Corporation Advera® Zeolite and SasolWax Sasobit® (WMA additives) were used in each mix to improve workability of the mix. WMA additives allow for reduced mix temperatures by lowering the viscosity and/or expanding the volume of the asphalt binder at lower temperatures.

Sustainability

Sustainability practices are extremely important, especially with the great emphasis on “going green” and reducing the negative impact on natural resources for future generations. In engineering, sustainability requires engineers and scientists to improve current practices to meet the needs of consumers without compromising those of future generations (U.S Environmental Protection Agency , 2009). If WMA and RAP technologies are perfected, aged HMA pavements will be able to be reclaimed, re-graded, and mixed with minimal virgin binder and aggregate than is conventionally used. The addition of additives, as mentioned before, will lower emissions which should reduce the negative effects.

Ethics, Health and Safety

Ethics, health, and safety all go hand in hand with WMA and RAP technologies. With any new technology, extra precautions must be taken to ensure the safety of vehicle travelers along the road. This research performed mechanical property testing to guarantee that the new RAP mix was equivalent or stronger than conventional HMA mixes.

No state allows complete RAP mix to be used without any additives, but studies such as this one, help close the gap between 100% hot mix and 100% warm mix reclaimed pavement. However, public safety is considered first and foremost in the feasibility analysis and it would be unethical to compromise public safety in the interest of research.

Economic Issues

Each of the aforementioned factors depends greatly on the economic feasibility of the design. If the positive environmental and sustainability factors do not outweigh the economical costs, the design will not be manufactured. This research evaluated the costs and benefits of 100% warm mix RAP as compared to 100% virgin mix. The comparison included the costs of warm mix asphalt additives, as well as the cost of burner fuel in plants and is included in the Results Chapter.

1 Introduction

The United States has 4 million miles of roads covered with asphalt pavement and about 4,000 asphalt plants across the country (National Atlas of the United States, 2008) (National Asphalt Pavement Association, 2009). Hot Mix Asphalt (HMA) is comprised of about 80% fine and coarse aggregates, 15% asphalt binder and 5% air voids (by volume) and is often mixed at temperatures of 149°C (300°F) to 176°C (350°F) (Anderson, Youtcheef, & Zupanick, 2009) (US Department of Transportation, 2008). HMA can be produced in two different plants: a batch plant or a drum plant. Batch plants produce HMA one "batch" at a time by drying and mixing the aggregates before moving the mix to another mixer and adding the asphalt (Communications, 2009). Drum plants are different because they dry the aggregate and then mix in the asphalt in a continuous manner.

Warm Mix Asphalt (WMA) is the process of using additives to reduce the mixing temperatures of HMA by 10°C (50°F) to 37.8°C (100°F) (Warm Mix Asphalt , 2009). The reduction in temperature is beneficial because it reduces the amount of fuel used to heat the mix, minimizes the expulsion of greenhouse gasses, and minimizes the paving temperature necessary in the field (Warm Mix Asphalt , 2009). Energy reductions have been shown to be over 54% when heating temperatures were reduced from 150°C to 130°C(Pakula & Mallick, 2007). However, the WMA process still uses 100% virgin materials.

Reclaimed Asphalt Pavement (RAP) uses recycled HMA pavement as the foundation for a new, re-graded, remixed pavement material. The process used in this research treated the RAP as a WMA and thus, included additives to reduce the compaction temperatures. Benefits of using RAP are similar to WMA in that they minimize temperatures and greenhouse gas emissions, but they also have been proven to reduce the cost of construction and the use of virgin natural materials and resources by recycling old material.

Maximizing the amount of RAP that can be incorporated in HMA technologies is ideal to minimize the amount of virgin materials used in pavement production. There is a limited amount of published material on studies that have used 100% RAP in the United States to produce a warm mix design. There are standards on how WMA processes should be run, but only a few about the effect of specifically using RAP with additives. In fact, in many states, regulations require that only 30% RAP can be added to HMA mixes because of concerns of using recycled material and asphalt binder as well as the lack of a regulated mix design procedure (Tao & Mallick, 2008). PQ Corporation Advera® Zeolite and Sasol Wax Sasobit® help reduce mixing and compaction temperatures while maintaining desired workability of asphalt concrete mixes and are considered appropriate additives for enabling HMA mixes with high RAP contents. For example, a recent experimental study performed at WPI confirmed the feasibility of making 100% RAP HMA base material with the aid of Sasobit® H8 or zeolite (Tao & Mallick, 2008).

The goal of this study was to evaluate the effects of warm mix additives on moisture susceptibility and bonding of asphalt with aggregates. By starting with RAP and using WMA technologies, we were able to close the gap between Hot Mix Asphalt (100% virgin materials) and 100% recycled materials.

To achieve this goal, the RAP properties were identified by determining the amount of aged binder and then modifying the amount of virgin binder added to the mix to achieve approximately 4% air voids on a 50 gyration compaction mix. Once the control mix was designed, a batch mix plant was simulated and additives were included to make a total of three mix designs: one control mix, one mix with Sasobit®, and one mix with zeolite. Three testing procedures, contact angle measurement, indirect tensile strength, and dynamic modulus, were employed to characterize moisture susceptibility of these mixes. For contact angle tests, slides were prepared to determine the contact angle between water and asphalt binder with different levels of zeolite and Sasobit®. Compacted cylindrical specimens were tested for their indirect tensile strength and dynamic moduli.

This report includes our findings relating dynamic modulus and indirect tensile strength of the 100% RAP mix design with contact angle analysis. Consideration of all three tests simultaneously offers insight into the moisture susceptibility of the mixes. Economic and environmental benefits were determined through a cost analysis of using Reclaimed Asphalt Pavement, Warm Mix Asphalt or Hot Mix Asphalt.

2 Literature Review

The use of Warm Mix Asphalt (WMA) technology for utilizing Reclaimed Asphalt Pavement (RAP) materials demands a complete understanding of WMA additives, asphalt binder, and the significance of physical properties such as compactability, air voids, rutting potential, and Surface Free Energy (SFE). This chapter discusses relevant research on warm mix additives on the SFE using contact angles and the moisture susceptibility of HMA mixes.

2.1 Warm Mix Asphalt

Hot Mix Asphalt (HMA) is typically produced in either batch or drum mix plants at a discharge temperature ranging from 137.8℃ (280°F) to 162.8℃ (325°F) (Button, Estakhri, & Wimsatt, 2007). Current and impending regulations regarding emissions are making it more attractive to consider greater reductions in HMA production temperature(Newcomb, 2006). These regulations have put pressure on the industry to reduce temperatures without compromising performance or economics.

In recent years, there has been some focus of producing WMA because the aim of this approach is to reduce the production temperature by using additives to increase the workability of binder at lower temperatures. Other benefits of WMA include a longer paving season, reduced emissions and the ability to travel over longer distance to paving site. Technology is now available to decrease HMA production temperature by 16°C (30°F) to over 55°C (100°F). These relatively new processes and products use various mechanical and chemical means to reduce the shear resistance of the mix at construction temperatures while reportedly maintaining or improving pavement performance (Newcomb, 2006).

In addition to the focus on WMA, there has also been an ever-increasing interest in using RAP with WMA technologies to decrease the environmental impacts by using less virgin material and reducing CO_2 emissions. According to Mallick et al., it is possible to manufacture mixes with 75% to 100% RAP with similar properties to HMA mixes through the use of additives (Mallick, Kandhal, & Bradbury, Using Warm Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement (RAP) Material in Asphalt Mixtures, 2008) (Mallick, Bradley, & Bradbury, 2007). Higher mixing and compaction temperatures age the binder in the RAP which has negative effects on the entire mix. The use of WMA additives helps reduce temperatures while achieving desired workability, thus enabling HMA to contain higher percentages of RAP.

2.2 Additives

A mix produced in the temperature range of 105°C to 135°C (220°F to 275°F) is considered to be WMA and the goal of such a mix is to obtain a strength and durability that is equivalent to or better than a HMA mix (Newcomb, 2006). Currently, a common way of achieving this is through the use of additives. All of the current WMA additives in use facilitate the lowering of production temperature by either lowering the viscosity and/or expanding the volume of the asphalt binder at a given temperature (Button, Estakhri, & Wimsatt, 2007)(Hurley & Prowell, Evaluation of Sasobit(R) for Use in Warm Mix Asphalt, 2005). By lowering the viscosity or expanding the volume of the asphalt binder, the aggregates are completely coated in asphalt binder at a lower than conventional temperature (approximately 150°C). Additives such as zeolite and Sasobit®, are "viable tools for reducing mixing and compaction temperatures" when added to HMA and allow an extended construction season by increasing the versatility of the mix (Hurley & Prowell, 2005)(Hurley & Prowell, Evaluation of Potential Processes for Use in Warm Mix Asphalt, 2006). Neither Sasobit® nor zeolite requires an extended cure period before opening the road to traffic (Hurley & Prowell, Evaluation of Sasobit(R) for Use in Warm Mix Asphalt, 2005)(Hurley & Prowell, 2005).

Reductions in temperature decrease energy costs and emissions but the lowered temperatures are often criticized. Pakula and Mallick found that the only impact on emissions is temperature, so additives such as Sasobit® may help reduce emissions (Pakula & Mallick, 2007). Hurley and Prowell evaluated Aspha-min® Zeolite and found that lower asphalt plant temperatures led to a 30% reduction in energy consumption and a 30-50% cut in overhead costs to the plant (Hurley & Prowell, 2005). Regardless of reduced energy costs, researchers are concerned that lower compaction temperatures used in WMA will reduce tensile strength, increase moisture damage, and increase the rutting potential (Hurley & Prowell, 2005)(Hurley & Prowell, Evaluation of Sasobit(R) for Use in Warm Mix Asphalt, 2005). The increased rutting potential may be due to the decreased age of the binder at lower mixing temperatures (Hurley & Prowell, 2005).

2.2.1 Sasobit®

Sasobit® is a wax additive known as an "asphalt flow improver" because it effectively lowers the viscosity of asphalt binder. With a lower asphalt viscosity, the working temperatures can be decreased by 18°C - 54°C (Hurley & Prowell, Evaluation of Sasobit(R) for Use in Warm Mix Asphalt, 2005). Made of Sasol Wax, Sasobit® is a long-chain aliphatic polymethlene hydrocarbon produced from the Fischer-Tropsch (FT) chemical process with a congealing temperature of 102°C and a melting temperature of 120°C. Sasobit® should be added at a rate of

0.8-3.0% by mass of binder for maximum effectiveness. When added in temperatures below 120℃, the Sasobit® strengthens the binder by forming crystalline network structures. However, the anti-aging properties of Sasobit® are thought to occasionally reduce the tensile strength of the asphalt.

The evaluation of rutting potential (permanent deformation), resilient modulus (elastic deformation), and compactability are important in determining the lifespan of the pavement. In general, Sasobit® reduces the rutting potential of asphalt. Tests show that as mixing and compaction temperatures decrease the rutting potential increases, which could be a result of the binder being less aged. (Hurley & Prowell, Evaluation of Sasobit(R) for Use in Warm Mix Asphalt, 2005). Regardless of this finding, Hurley and Prowell found that mixes with Sasobit® were less affected by decreased temperatures than control mixes with the same amount of asphalt binder. There is some concern about the effects of Sasobit at lower temperatures because below 80℃ – 90℃ (176°F-194°F) it forms a crystalline network and increases the stiffness of the mix, which can lead to an increased potential of thermal cracking. However, Mallick, Kandhal and Bradbury suggest adding a lower grade binder to RAP with Sasobit® because the lower grade binder can actually reduce the stiffness of Sasobit at lower temperatures (Mallick, Kandhal, & Bradbury, Using Warm Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement (RAP) Material in Asphalt Mixtures, 2008). The addition of Sasobit® does not affect the resilient modulus when compared to other asphalt mixes with the same performance grade (PG) binder. Sasobit® improved compactability of mixtures in the Superpave Gyratory Compactor (SGC) and vibratory compactor and air voids were reduced by 0.87% in temperatures as low as 88°C (Hurley & Prowell, Evaluation of Sasobit(R) for Use in Warm Mix Asphalt, 2005) Adding Sasobit® reduced air voids and lead to greater compaction and longer lasting pavements(Keeches & LeBlanc, 2007).

2.2.2 Zeolite

Advera® WMA Zeolite, often shortened to just zeolite, is an additive ideal for typical paving projects and is produced by PQ Corporation with headquarters in Pennsylvania. Another brand more commonly used outside of the United States, Aspha-min® Zeolite, is produced by Eurovia Services GmbH in Bottrop, Germany. Zeolite is composed of hydro-thermally crystallized framework silicates with spaces that allow large cations and are perfect for adjusting to moisture levels without damaging the asphalt (Hurley & Prowell, 2005). Both brands are practical in WMA with only minor differences (US Department of Transportation Federal Highway Administration, 2008).

- Advera® is a finer grade zeolite than Aspha-min® and passes through a 750mm (No. 200) sieve.
- PQ Corp. recommends that Advera® be added at 0.25% by weight, while Eurovia suggests Aspha-min be added at 0.3% by weight.
- Advera has 18-21% of its mass as water, while Aspha-min is 21% water.
- Advera reduces HMA production temperatures of HMA by 50°F -70°F and Aspha-min reduces production temperatures by 54°F.
- Advera is released in temperatures above 210°F while Aspha-min is released in 185°F-360°F.

Zeolite is known as a foaming additive because it foams when it is added to the mix and comes in contact with the binder. After the binder is added in a drum plant, Advera® Zeolite is added as a powder through the fiber port of the plant (PQ Corp, 2007). Advera® is naturally 18-21% moisture and this small amount of water (about 0.03% of the entire mix) immediately turns to steam at temperatures above 98.9°C (210°F) and mixes with the binder or is compressed out of the mix. The addition of this additive increased the volume of the binder slightly but improves the workability of the mix. Any remaining moisture is absorbed by the Advera®. The ability to "lose and absorb" water and other liquids is positive, especially with RAP, but has been critiqued because the moisture does not always completely evaporate during mixing at lower temperatures (Hurley & Prowell, 2005). When Zeolite is added to binder between 82°C and 182°C, 21% of water by mass is released but the remaining moisture may lead to increased vulnerability to moisture damage (Hurley & Prowell, 2005).

Physical testing has shown zeolite to improve the compactability at temperatures as low as 88°C with an air void reduction of 0.65% (Hurley & Prowell, 2005) (PQ Corp, 2007). Similar to Sasobit®, zeolite does not affect the resilient modulus or increase the rutting potential of the asphalt pavement. Hurley and Powell recommend optimizing the asphalt content before the addition of zeolite and then taking additional samples to adjust for the additive.

Hurley et. al. performed a field study in Orlando, Florida with Aspha-min® aided warm mix RAP put down at 66°C and a control RAP mix put down at temperatures between 71°C and 82°C (Hurley & Prowell, 2005). Cores were taken after the pavement cooled and one year later. Laboratory testing completed on the cores determined that there were no significant differences between the RAP control and the warm mix. The density and air voids were essentially equal with exception to the gyratory air voids where the warm mix voids were slightly higher. No differences in strength gain were present and the warm mix and control were equally resistant to moisture damage.

2.3 Moisture Susceptibility

Moisture susceptibility is a tendency of asphalt mixes to lose the bond between asphalt and aggregate and is one of the biggest concerns with pavement performance, whether it is hot mix, warm mix, or RAP (Hunter, 2001). Moisture damage happens when the presence of moisture through air voids negatively affects the strength and durability of the HMA (Zollinger, 2005). Two types of moisture damage can occur: adhesive failure and cohesive binder. Adhesive failure is between the binder and aggregate while cohesive failure is the reduced strength of the binder through moisture damage (Zollinger, 2005).

There is an increased possibility for moisture damage when using WMA additives due to the lower compaction temperature (Hurley & Prowell, Evaluation of Potential Processes for Use in Warm Mix Asphalt, 2006). The results suggest that this is possibly because lower mixing and compaction temperatures can result in incomplete drying of the aggregate. Hurley et. al recommend that moisture sensitivity testing be performed at proposed field production temperatures to ensure the longevity of the pavement (Hurley & Prowell, Evaluation of Potential Processes for Use in Warm Mix Asphalt, 2006). Several different procedures have been used to evaluate moisture susceptibility.

2.3.1 Indirect Tensile Strength

Indirect tensile strength (ITS) is a very common performance test used in the pavement industry. ITS testing offers a reliable indication of the crack potential for a mix. Testing a mix with and without moisture conditioning can aid in measuring the moisture susceptibility of the mix (Washington State Department of Transportation, 2009). A specimen is loaded diametrically to a cylindrical specimen until failure; a high strain at failure suggests the mix will resist cracking (Mallick & El-Korchi, 2009).

In 1998, Maine DOT accepted the Superpave method of mix design. This method recommends considering the tensile strength ratio (TSR) of the moisture conditioned and unconditioned samples as the most appropriate measure of moisture susceptibility (Washington State Department of Transportation, 2009). This conventional measure of moisture susceptibility can be reinforced by the consideration of contact angle measurements and dynamic modulus results, which were proposed recently to be promising alternatives to assess moisture susceptibility of asphalt mixes (Tao & Mallick, 2008).

2.3.2 Surface Free Energy and Wettability

Two determinations of moisture susceptibility are the wettability and adhesion of the binder. Greater wettability leads to less adhesion and greater moisture susceptibility. Wasiuddin et al.

used the Surface Free Energy (SFE) Method to determine contact angles between two asphalt binders (PG 64-22 and PG 70-28) and three liquid solvents (water, glycerine and formamide) with known properties (Wasiuddin). The binders were tested with two additives added as percentages by weight: Sasobit® (0%, 2%, 4%, 8%) and Aspha-min® (0%, 1%, 4%, 6%). The SFE is calculated using the Young-Dupre equation and Good's postulation shown in Equation 1.

$$\Gamma_L(1+cos\theta) = -2 * \sqrt{\Gamma_S^{LW}\Gamma_L^{LW}} - 2 * \sqrt{\Gamma_S^{-}\Gamma_L^{+}} - 2 * \sqrt{\Gamma_S^{+}\Gamma_L^{-}} \qquad 1$$

where,
Γ_L^{LW}, Γ_L^{+}, and Γ_L^{-} = SFE components of liquid solvent,
Γ_S^{LW}, Γ_S^{-}, and Γ_S^{+} = SFE components of asphalt binder, and
θ = Contact angle.

Wassiuddin et.al. defined wettability as the spreading coefficient of the chosen solvents dropped on the asphalt binder with and without additives. The spreading coefficient is determined using Equation 2.

$$S_{L/S} = \Gamma_S - \Gamma_{SL} - \Gamma_{LV} \qquad 2$$

where,
$S_{L/S}$ = Spreading coefficient of liquid L on solid S,
Γ_S = Advancing/wetting SFE of solid S, ergs/cm^2,
Γ_{SL} = Advancing/wetting solid-liquid interfacial energy, ergs/cm^2, and
Γ_{LV} = Advancing/wetting SFE of liquid L, ergs/cm^2.

Wasiuddin et. al. found that Sasobit® reduced the adhesion and increased wettability. The increase in wettability may have been due to the hydrophobic (water repellent) qualities of the Sasobit® wax. Aspha-min® had an insignificant effect on adhesion and wettability of the binder (Wasiuddin, Zaman, & O'Rear, 2007).

2.3.3 Dynamic Modulus

A common physical property of interest is modulus. Modulus is the ratio of stress over strain during a loading sequence. Dynamic modulus (|E*|) is the absolute value of the complex modulus of a material (Mallick & El-Korchi, 2009). Evaluating the |E*| of a mix is a suitable consideration in the quest of moisture susceptibility because it is an indicator of the viscosity of the mix (Washington State Department of Transportation, 2009). Evaluating |E*| before and after moisture conditioning can aid in supporting the TSR results for a mix, in turn supporting hypothesis of moisture susceptibility of different mixes.

The research presented in the Literature Review assisted in the formation of the following methodology and design procedure. A basic understanding of moisture susceptibility can be gained by conducting contact angle measurements, dynamic modulus and indirect tensile testing.

3 Methodology

The goal of this research was to evaluate the effect of WMA additives on moisture susceptibility of HMA mixes containing 100% RAP. To achieve this, the researchers measured contact angles of various asphalt binders and determined the dynamic modulus and indirect tensile strength of various warm mix designs with and without additives. The research methodology is presented in Figure 1.

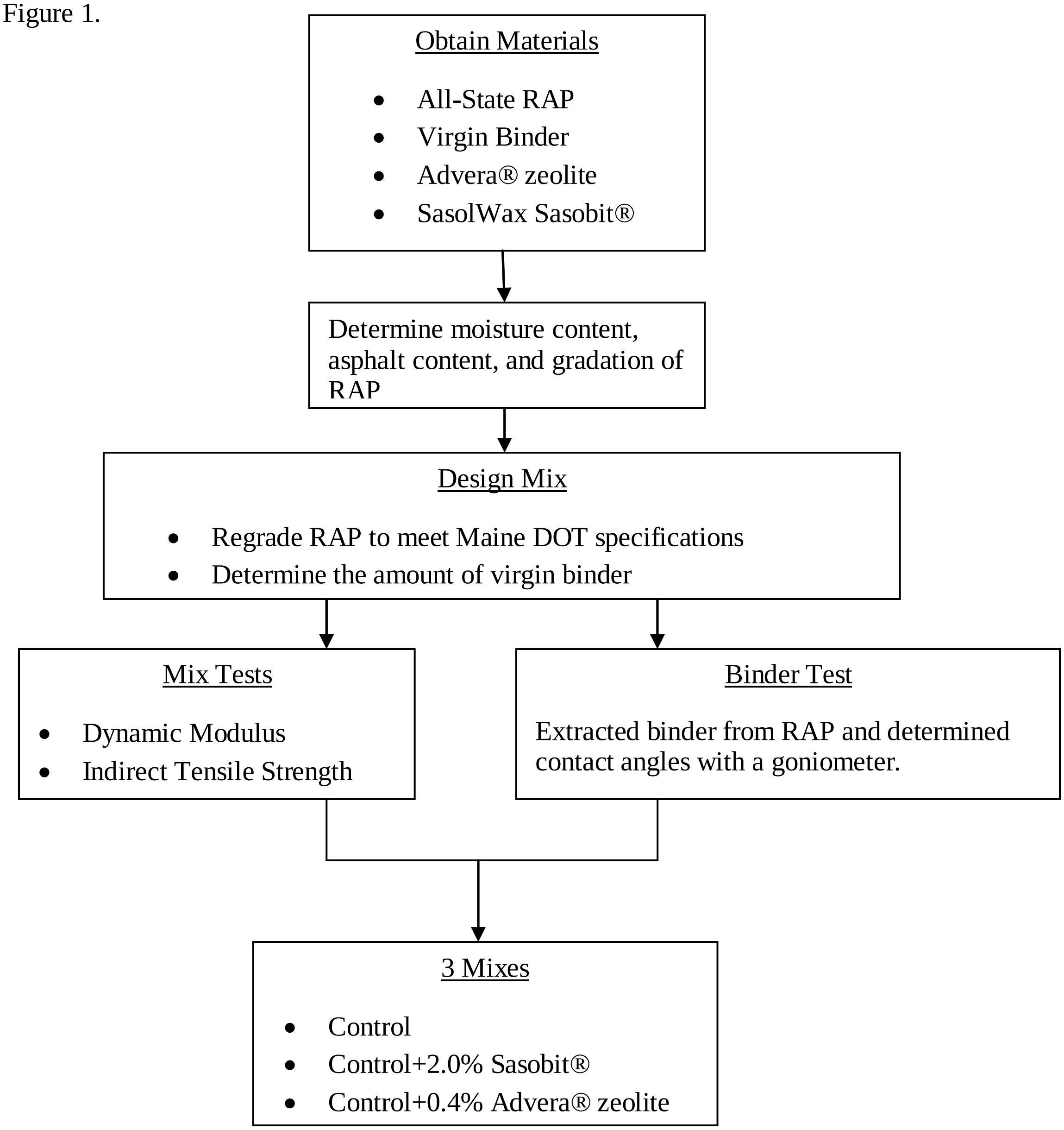


Figure 1: Flow Chart of Procedures

3.1 Re-gradation of RAP

The purpose of re-grading the All State Asphalt, Inc (ASA, Inc) RAP was to meet gradation standards set forth by the Maine Department of Transportation (Maine DOT), which began by characterizing the RAP, grading the RAP, and then re-combining the RAP. The RAP used in this study was pulled from a stockpile in Holliston, Massachusetts that consisted of RAP milled from Eastern Massachusetts roads. The RAP was milled from the surface course of low to medium volume roads. The asphalt binder of all the RAP in the stockpile was originally AC20 (approximately PG64-28) grade asphalt binder. The RAP re-gradation process consisted of the following steps:

1. Three batches of RAP, all weighing approximately 1000 grams, were prepared.
2. The Moisture Content of each batch was determined.
3. The Asphalt Content of each batch was determined in accordance with *ASTM D 6307 – 98: Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method*.
4. A complete washed sieve analysis was run on each batch in order to determine the gradation of the RAP, in accordance with *AASHTO T 27-93: Sieve Analysis of Fine and Coarse Aggregate*.
5. The entire available RAP was separated into four fractions in order to determine the feasibility of developing a mix design in accordance with aggregate size standards set forth by Maine DOT for a 50 gyration mix design. Fraction definition is shown in Table 1. Fractions 2 and 3 were most predominant among the ASA, Inc. RAP.

Table 1: RAP Fractions

Fraction Number	Passing Sieve	Holding Sieve
1	----	12.5 mm (1/2 in)
2	12.5 mm (1/2 in)	2.36 mm (No. 8)
3	2.36 mm (No. 8)	0.075 mm (No. 200)
4	0.075 mm (No. 200)	Pan

Figure 2 shows a visual comparison of the three fractions used in the final mix design.

Figure 2: Fractions 1 through 3 (from left to right)

6. The sieve analysis (gradation) results of the burnt RAP and the fractioned RAP were plotted. The percent passing was plotted against the sieve size raised to the .45 degree. The super-imposed plots, Figure 3, show the fines were not adequately represented in

Fraction 4. As a result, the two prominent fractions needed to be burnt, washed, and graded in order to determine the distribution of the fines.

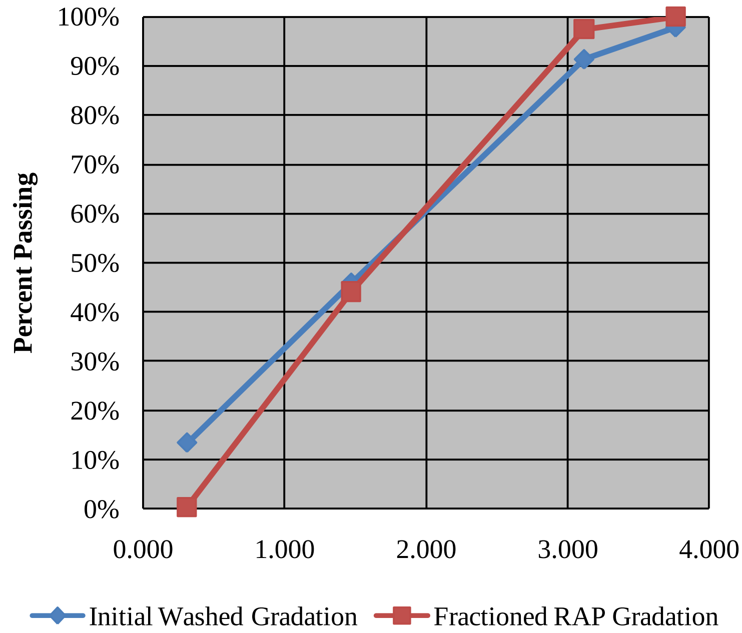


Figure 3: Gradation Comparison

7. Steps 2 through 4 were repeated using two batches each from Fraction 2 and 3 of approximately 1000 grams.
8. The gradation results of the fractioned RAP, the burnt fractioned RAP, and the target for an Maine DOT 50 gyration mix design were plotted in order to determine the percentage of each fraction needed. The percent passing was plotted against the sieve size raised to the .45 degree. The percentages of the burnt fractioned RAP curve were adjusted until the curve resembled the target gradation curve in a satisfactory manner.
9. The available ASA, Inc RAP was re-graded by re-combining the RAP using the percentages of each fraction determined in step 8, only Fractions 1,2, and 3 were used in the re-gradation. The final mix of RAP included the desired percentage of each fraction and was in accordance with the gradation standards set-forth by the MAINE DOT for a 50 gyrations mix design.

3.2 Asphalt Content Approximation of Re-graded RAP

To limit the amount of material being used for characterization, the asphalt content of the re-graded RAP was approximated. This approximation was used to gain a base point to build the mix design for 4% air voids.

1. The asphalt content of Fraction 2 and 3 was determined in accordance with *ASTM D 6307 – 98: Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method* during the preparation of the fractions for a complete sieve analysis.

2. The asphalt content of Fraction 1 was estimated to be 2.5%. This fraction was not burnt because it was the control fraction.
3. The amount of asphalt was approximated by considering the percent of each fraction in the final re-gradation, determined in Section 3.1, and the amount of asphalt in each fraction.

$$\%AC_{re-graded} = (\%Fract1)\left(\%AC_{fract\ 1}\right) + (\%Fract2)\left(\%AC_{fract\ 2}\right) + (\%Fract3)\left(\%AC_{fract\ 3}\right) \quad (3)$$

3.3 Mix Design for 4% Air Voids

In order to create a mix design of 4% air voids, several different mixes at different temperatures, shown in Table 2, were prepared and the air voids were calculated. The percent air voids was determined by modification to *AASHTO T269: Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixes*. The AASHTO procedure was modified by determining the bulk specific gravity (BSG) and theoretical maximum density (TMD) of the mixes using CoreLok® procedures.

Table 2: Percent Air Void Mix Variations

Sample ID	Temp (°C)
100% Regraded RAP	125
100% Regraded RAP	150
Regraded RAP + 1.5% SH	125
Regraded RAP + 1.5% SH	130
Regraded RAP + 1.0% VB	150

The percent of air voids in the samples were calculated using Equation **4**, which considers the TMD and BSG of a sample in order to determine the voids present in the sample.

$$\%Air\ Voids = \left[1 - \frac{BSG}{TMD}\right] * 100 \quad (4)$$

3.4 Determination of the Total Amount of WMA Additives

For this study three mix variations were analyzed. The control mix contained RAP and 1.0% PG58-28 Virgin Binder and the second and third mixes were comprised of the RAP with specified amounts of either Sasobit® or zeolite. Typically the amount of virgin binder to be included in a mix design would need to be determined through trial and error. However, this study was a continuation of a Tao and Mallick study, so 1.0% was considered appropriate based on that research. In order to determine the correct amounts of binder or additives to add to the RAP, the exact asphalt content had to be established.

3.4.1 Determination of Asphalt Content

Three batches of re-graded RAP of approximately 1000 grams were burnt and the asphalt content determined in accordance with *ASTM D 6307 – 98: Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method*. It was found that 3.38% of the total re-graded mass of RAP was aged-binder (AB).

3.4.2 Adding Virgin Binder (VB)

The control for this study is a base mix of RAP with 1.0% PG58-28 VB added. For this mix preparation, the amount of VB added is based on the amount of aggregates in the mix. Knowing the amount of aged binder (AB) in the mix, the amount of VB to be added can be determined using Equation **5**. After burning the RAP, the aged asphalt content was determined to be 3.38%. Generally, the mass of the aggregates in an HMA mix are assumed to be 100% of the mass considered for asphalt content determination. A sample calculation is shown in conjunction with Equation **5**.

$$Target\ Asphalt\ Content = \frac{AB + VB}{RAP + VB} = \frac{3.38 + 1.0}{100 + 1.0} = 4.3\% \qquad 5$$

3.4.3 Adding Sasobit® to Control Mix

For testing 2.0% Sasobit® was added to the control mix and was calculated using Equation **6**. The amount of Sasobit to be added was calculated by considering the mass of the entire asphalt binder.

$$SS(grams) = (\%\ of\ Sasobit)(0.0538)[RAP(grams) + VB(grams)] \qquad 6$$

3.4.4 Adding Zeolite to Control Mix

When a mix containing zeolite was prepared, the total sample mass of the control mix was considered: aggregate, AB, and VB. For testing 0.4% zeolite was considered and Equation **7** was used to determine the required mass of the additive.

$$Zeo(grams) = \%\ of\ zeolite * [RAP + VB](grams) \qquad 7$$

3.5 Contact Angles

Contact angles were analyzed to determine the effects of virgin asphalt binder and RAP with and without additives. A 1% by mass proportion of virgin binder was added to all samples because it was part of the mix design used for physical testing. The asphalt binder was extracted from the ASA, Inc RAP, slides were prepared and a ramé-hart Model 100-00 Goniometer was used to obtain contact angle measurements.

3.5.1 Extraction of Asphalt Binder from RAP

In order to obtain aged binder from the ASA, Inc RAP for the contact angle slides, the aged binder was extracted. To ensure the extraction process did not negatively affect the slide preparation an HMA virgin mix was also extracted. The extracted asphalts were placed in vials and the desired combinations of aged binder, virgin binder, and WMA additives were obtained. The extraction apparatus presented in Figure 4 performed all extractions in this study.

1. The binder was extracted from the mix.

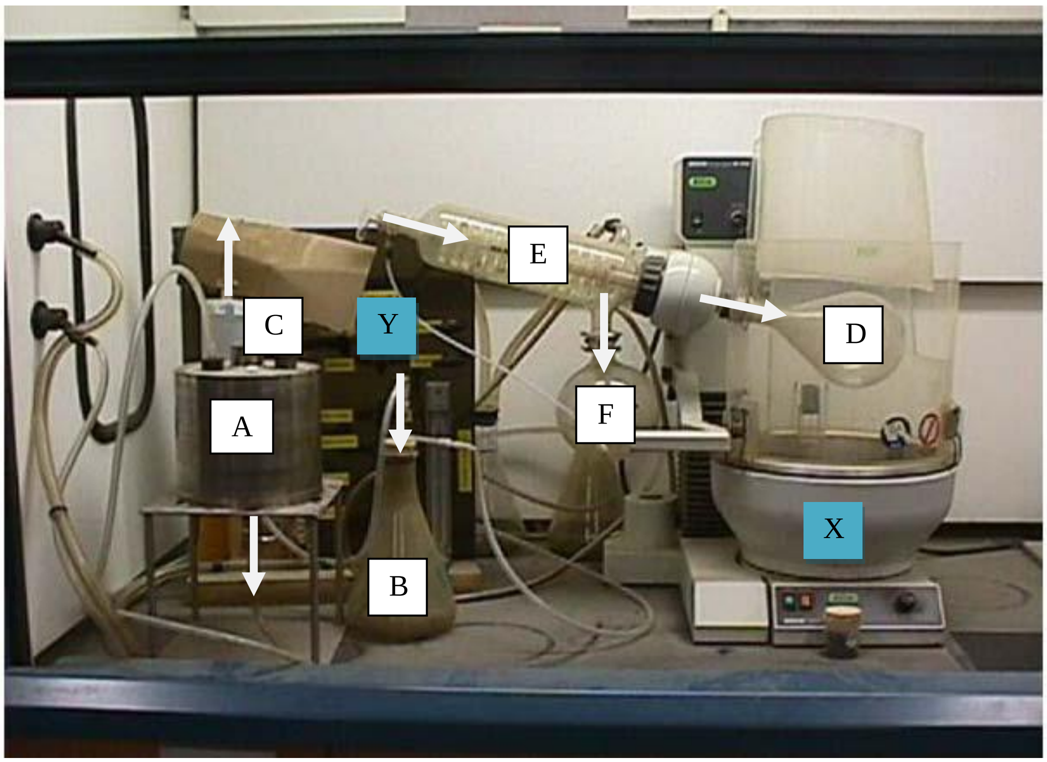


Figure 4: Extraction Apparatus

A: extraction vessel
B: holding flask (1) for toluene/binder mixture
C: filter to catch fines
D: holding flask (2) (contains extracted asphalt after distillation)
E: distillation column
F: holding flask (3) for distilled toluene
X: oil bath
Y: control panel for regulating flow of vacuum and nitrogen to apparatus

The extraction process began by placing a specified amount the RAP in the extraction vessel (A) with a specified amount of toluene. A motor that is attached to A rotates the vessel for a specified time that corresponds with the amount of toluene added. A was then placed vertically in a stand and the quick release valve was attached to tubing. This allowed the toluene/binder mixture to flow into the first holding flask (B). From B the mixture was conveyed through the filter (C) and stood in the second holding flask (D). D rotates in the oil bath (X) as the toluene was distilled out of the mixture through the Rotovaps distillation column (E) and stood in the third holding flask (F). This process was conducted to comply with the procedure outlined in *SHRP D B-006: Standard Practice for Extraction and Recovery of Asphalt Cement for Rheological Testing*. .

2. The extracted binder was placed in vials, approximately 5 grams was placed in each vial.
3. The additives were placed in the vials and the contents of each vial are presented in Table 3.

Table 3: Extraction Vial Preparation

ID #	Sample Content
1	Aged Binder(AB) + 1.0%Virgin Binder(VB)
2	AB + 1.0%VB + 2.0%SS
3	AB + 1.0%VB + 0.4%zeolite

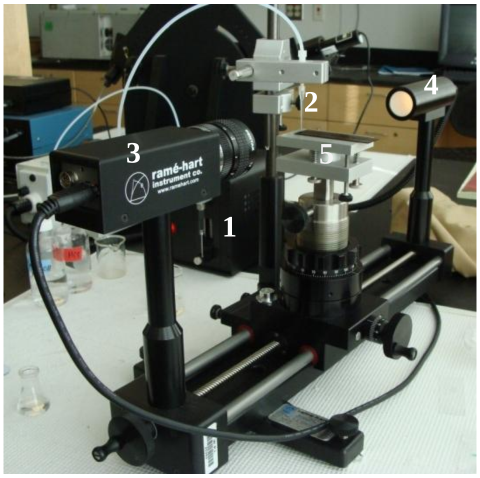
4. The binder mixes were then diluted with 20 mL of toluene and rotated 20 revolutions per minute for about 48 hours or until the mix was completed dissolved.

3.5.2 Slide Preparation

Once the mix was fully dissolved, the slides were prepared using a centrifuge on the slowest speed. The slide was placed on the stage and 3 mL of the dissolved asphalt binder was pulled into a pipette. After 6 seconds of spinning, the 3 mL was dispensed on the slide. At 30 seconds, the centrifuge was stopped and took about 18 seconds to completely stop rotating. After the slide was prepared, it was removed from the centrifuge and the base was cleaned so it would not stick to surrounding surfaces. Slides containing Sasobit® were heated to 70° for approximately 20 minutes to dissolve the Sasobit® before they were put into the centrifuge.

3.5.3 Goniometer

Once the slides were prepared, contact angles were measured using the ramé-hart Model 100-00 Goniometer, shown in Figure 5, in the Surface Characterization Laboratory in Gateway Park at WPI. The goniometer uses the sessile drop method to determine the contact angle of liquids, called probe liquids, with known properties. Water, a popular probe liquid, was used in this testing because it does not change the chemical properties of the asphalt binder and its surface energy components are known.



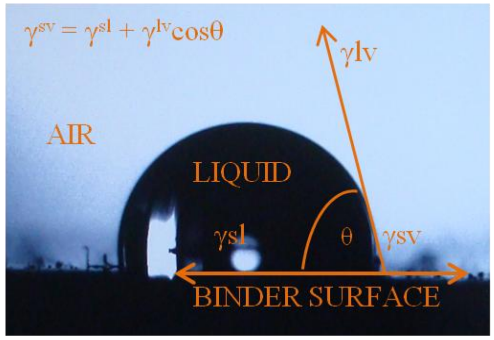
Label	Instrument
1	Ramé-hart Automated Dispensing System
2	Pipette for dispensing onto slide
3	Camera
4	Backlight
5	2x3 leveling specimen stage

Figure 5: Goniometer

The goniometer used a live-feed camera and DROPimage Standard software to determine the contact angles.

1. The Auto Dispensing System, backlight and camera were turned on before the software was opened and before any contact angles were taken, the micro-pipette was rinsed out. The program has a "Drop Volume Control" menu so the user can determine the appropriate amount of rinse cycles to ensure a sterile process.
2. After the pipette is rinsed, in the same menu, "FILL" was selected to fill the pipette with the probe liquid. If using a probe liquid other than water, there should be an air bubble between the water present in the pipette and the probe liquid to ensure that the probe liquid does not dilute or mix with the water. This air bubble was obtained by pressing "Input step" an appropriate number of times so as to create a visible air bubble in the pipette.
3. Next the test slide was placed on the stage and the camera was focused. When necessary, the backlight intensity was altered to get the best contact angle reading.
4. The pipette was pivoted over the slide so that both the slide and the pipette tip were visible on the computer screen as a live feed.
5. Using the "Drop Volume Control" menu, droplet volumes of between 1 microliters (μL) and 3 μL were selected and dispensed (by pressing the "Output Step" button) on the slide.
6. Contact angles were measured using limits set by the computer program. In the "Contact Angle" Options menu, the Circle Method was selected. Left, right, top, and bottom limits were set by the user to determine the Region of Interest (ROI). After the ROI was determined, the user pressed "START" and then "MEASURE" in the "Contact Angle" toolbar. Once the contact angle reading appeared in the "Stored Results" table, "STOP" was pressed to reset the system and prepare for the next reading.

   Calculations were computed entirely by the program and presented in tabular form. Each table presented calculated left and right contact angles, mean contact angle measurements, and the height, and width of the droplet. Contact angles were measured using Young's Equation, shown in Figure 6. The figure shows the right contact angle, which is calculated using the free energy between the solid, liquid and air vapor.



θ is the contact angle
γ^{sv} is the solid/liquid interfacial free energy
γ^{sl} is the solid surface free energy
γ^{lv} is the liquid surface free energy

Figure 6: Contact Angle Conception

7. After the row was filled and no more contact angles could fit on the slide, it was removed and air-dried. It was important not to wipe the slides clean because the asphalt was thin and could be easily rubbed off.

The sessile method depends greatly on the homogeneity of the slides. A hydrophobic liquid, shown in Figure 6, produces a high contact angle and thus low wetting and low surface energy. Hydrophilic liquids produce a low contact angle, and thus high or complete wetting with high surface energy. With asphalt, it is desirable for the liquids to be hydrophobic so as to not damage pavement during extreme weather conditions.

3.5.4 Contact Angle Analysis

Statistical analysis is important to any experiment. Analysis of contact angles included determining average contact angles, calculating standard deviation, using a t-distribution to determine a 95% confidence level and performing an Analysis of Variance (ANOVA).

Confidence testing is used to determine how likely a value is to be in a certain interval. A 95% confidence means that 95% of the time, the contact angle measured will be in the range specified. Accordingly, 5% of the time, the contact angle will not be within the specified range.

ANOVA is a hypothesis test that was used to determine if there was a statistical difference in contact angles among different asphalt binders and warm mix asphalt (Petruccelli, Nandram, & Chen, 1999). The ANOVA is illustrated in Table 4 for easier conception but the basic principle is that if the calculated F was equal to or greater than $F_{critical}$, then the null hypothesis would have been rejected. On the contrary, if calculated was less than $F_{critical}$, the null hypothesis could not be rejected.

Table 4: Hypothesis Testing

H_o	$\mu = \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$	If this is true, values are statistically the same.
H_A	$\mu \neq \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4 \neq \mu_5$	If this is true, values are statistically different and the additives have a significant impact on contact angles.

The calculated F value must be compared to the tabulated critical F value. If $F_{critical}$ was equal to or less than the calculated F value, the null hypothesis could be rejected and all of the compared values would be statistically different. If $F_{critical}$ was larger than the calculated F value, then the null hypothesis could not be rejected and therefore there would be no statistical difference between values.

Initially a Treatment Table, shown in Table 5, was made. The number of treatments was the number of slides that were compared and the sum of the values for each treatment was used to determine the sum of the squares.

Table 5: Sample Treatment Table

Treatment (T) →	Slide 1	Slide 2	Slide 4	Slide 5
	$X_{1,1}$	$X_{2,1}$	$X_{4,1}$	$X_{5,1}$
	$X_{1,2}$	$X_{2,2}$	$X_{4,2}$	$X_{5,2}$
	$X_{1,N}$	$X_{2,N}$	$X_{4,N}$	$X_{5,N}$
T totals	$\sum X_{1,1\ldots}\ X_{1,r^*}$	$\sum X_{2,1\ldots}\ X_{2,r}$	$\sum X_{4,1\ldots}\ X_{4,r}$	$\sum X_{5,1\ldots}\ X_{5,r}$

*r is the number of X values in each treatment. r can be different for each treatment.

Once the Treatment Table values were calculated, values in the ANOVA table, Table 6, were calculated to determine the calculated F.

Table 6: Standard ANOVA Table

Source	DF	SS	MS	F
Treatments (T)	k-1	SS_T	MS_T	$\frac{M_{ST}}{MS_{error}}$
Within	N-k	SS_{ERROR}	MS_{ERROR}	
Total	l=N-1	TSS		

Where:

T = treatment, or the number of slides tested
DF = degree of freedom

k = number of readings in each treatment
N= total number of treatments, ∑k

SS_T = sum of the squares between treatments = $\sum \frac{T_i^2}{r} - \frac{T_{total}^2}{N}$

v = variance = standard deviation squared = σ^2

SS_{errpr} = variability between T sum of the squares = σ^2/(N-1)

MS_T & MS_{error} = sum of the squares divided by the degree of freedom

F = $\frac{M_{ST}}{MS_{error}}$

$F_{critical}$= tabulated critical values of which to compare calculated F values, the area under a curve with k & l degrees of freedom

3.6 Sample Preparation and Application

The dynamic modulus (|E*|) and indirect tensile strength (ITS) specimens were used for both tests. Reusing samples lowered the amount of RAP needed for this study. Table 7 shows the sample specification and which test(s) each sample was used for. The |E*| are not compromised therefore one of the samples can be cut for the IDT.

Table 7: Compacted Sample Use for |E*| and IDT Tests

Sample #	**1, 2, 3**				**4**			
Test Procedure	|E*|		IDT		|E*|		IDT	
Moisture Conditioning	With -out	With	With -out	With	With -out	With	With -out	With
RAP + 1.0% VB	X	X		X			X	
RAP + 1.0% VB + 2.0% SS	X	X		X			X	
RAP + 1.0% VB + 0.4% Z	X	X		X			X	

3.7 Dynamic Modulus

In order to determine the dynamic modulus for the three different mixes of interest, samples were prepared in accordance with *Appendix 2* of *|E*| - DYNAMIC MODULUS: Test Protocol – Problems and Solutions*. The test was performed in a Universal Testing Machine, equipped with a loading cell and a computer containing a ShedWorks® software package for data collection, following the modified procedure that follows.

1. Twelve, four for each mix of interest, 170 mm (6.69 in) high six inch diameter specimens were prepared in a Superpave Gyratory Compactor with height-control mode in accordance with *AASHTO T 312 Standard Method of Test for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor* with modifications to compaction temperature for WMA.

2. Four samples, six inch diameter gyrated to 170 mm inch height, of each mix were prepared. All mixes were compacted with a target temperature of 125°C.
3. The BSG of each sample was determined using the CoreLok®.
4. Each sample was cored using a 4 inch coring rig.
5. The rough ends of the cylindrical specimen were sawed off using a double blade saw to reach a smooth height of 152.4 mm (6.00 in).
6. Mounting studs for the axial Linear Variable Differential Transformers (LVDTs) were attached using quick setting epoxy in accordance with the mounting specifications provided by ShedWorks, Inc. for the Dynamic Modulus testing using the Universal Testing Machine. Mounting instructions can be found in Appendix 1: LVDT Sample Mounting for Dynamic Modulus Testing

Figure 7: Mounted |E*| Sample

7. The samples were tested at four temperatures. At each temperature the samples were tested under four loading frequencies, with a different specified load applied at each temperature to achieve appropriate amount of elastic deformation in the samples. The testing conditions are summarized in Table 8.

Table 8: |E*| Testing Conditions

Temperature (ºC (ºF))	Frequency (Hz)	Peak Load (lb)	Contact Load (lb)
-10 (14)	10, 5, 1, 0.1	2500	125
4.4 (40)	10, 5, 1, 0.1	1200	60
21.1 (70)	10, 5, 1, 0.1	600	30
37.8 (100)	10, 5, 1, 0.1	250	13

The testing was performed in a Universal Testing Machine that consisted of a small environmental chamber equipped with a loading cell within a large environmental chamber, depicted in Figure 8.

Figure 8: Large Environmental Chamber (left) and Small Environmental Chamber (right)

8. Each sample was tested twice, before and after accelerated moisture conditioning. Moisture conditioning was performed in accordance with *GDT 66, section j* (Georgia Department of Transportation, 2008). In this study, 6 inch height samples were used. A simplified procedure follows.
    a. The dry mass of the samples was determined.
    b. The saturated-surface dry (SSD) mass of the samples was determined.
    c. The samples were allowed to dry completely overnight and vacuum sealed using the CoreLok®, bag set up and sealed sample shown in Figure 9.

Figure 9: CoreLok® Bags (left) and Sealed Sample (right)

    d. The vacuum sealed samples were placed in water, bag opened under water, and allowed to saturate for 30 minutes, shown in Figure 10.

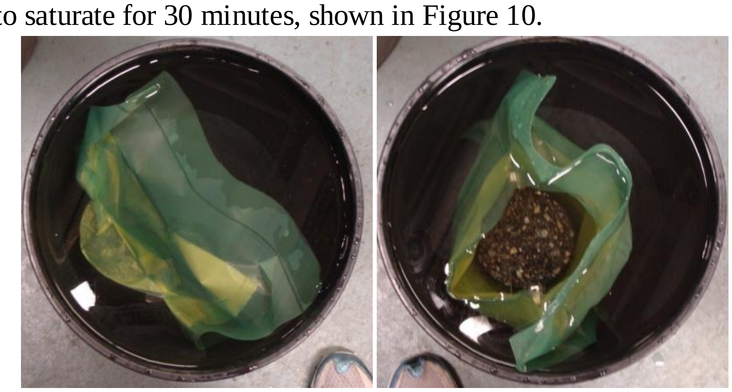


Figure 10: Submerged Saturation of the Vacuumed Sealed Sample

    e. The vacuum saturated SSD mass of the samples was then determined.

f. The samples were then placed in a zip-lock bag (gallon size) with approximately 10 mL of water and sealed, shown in Figure 11.

Figure 11: Bagged Sample for Freezing

g. The samples were moved to a freezer, that held a temperature of –18° ± 2°C (–0.4° ± 3.6°F), for at least 15 hours.
h. After ample freezing time the samples were moved to a warm water batch, that held a temperature of 60ºC (140ºF), for at least 24 hours with the bags open to allow the warm water to penetrate the samples.
i. After the freeze thaw process the samples were set out to dry and the mounts were re-fitted if necessary.

The results of the test are presented by the ShedWorks® software in a Microsoft Office Excel2007® worksheet containing the deformation readings of the LVDTs at each frequency. This data were then organized by frequency and interpreted by a MatLAB® program developed at WPI. The dynamic modulus and phase angle were then transferred to an Excel® workbook for analysis.

3.8 Indirect Tensile Strength Test (ITS)

Indirect Tensile Strength (ITS) testing was performed in accordance with *AASHTO T283-89 Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage* on a universal testing machine that was retrofitted from pneumatic to hydraulic actuation by Shedworks, Inc. Six samples were produced and each 4-inch diameter, 6-inch thick cylinder was cut into three smaller cylinders using a double blade saw to yield a 4-inch diameter 2-inch thick disc. This resulted in nine unconditioned and nine conditioned specimens. The conditioned specimens had been previously moisture conditioned during the dynamic modulus testing in accordance with *GDT 66* (outlined in Section 3.7).

The ITS requires applying a compressive load on a cylindrical specimen, in this case a 4-inch diameter 2-inch thick disc. The specimen was loaded until failure and the IDT was calculated using Equation 8. Where P is the maximum load, d is the diameter of the specimen, and t is the thickness of the specimen.

$$IDT = \frac{2 * P}{\pi d t} \quad 8$$

Graphical outputs from Shedworks, Inc software of the forces applied to the samples are in Appendix 2: Indirect Tensile Strength Shedworks® Output

The methodology presented in this chapter assisted in the exploration of the effects of warm mix asphalt additives on moisture susceptibility in reclaimed asphalt pavement. The results chapter presents the findings of this research from start to finish.

4 Results

The results of the research are presented in this Chapter. Moisture susceptibility was explored through the research of contact angles between water and asphalt binder and the measurement of indirect tensile strength and dynamic modulus of compacted samples.

4.1 RAP Re-gradation

The process of re-grading the ASA, Inc RAP to meet gradation standards set forth by the Maine DOT resulted in the RAP fractions being combined to follow the gradation plotted in Figure 12. The Burnt RAP Gradation curve and the RAP Gradation curve are linked in order for the fines to be realistically represented in the RAP. The Burnt RAP Gradation line was attempted to meet the target as closer as possible.

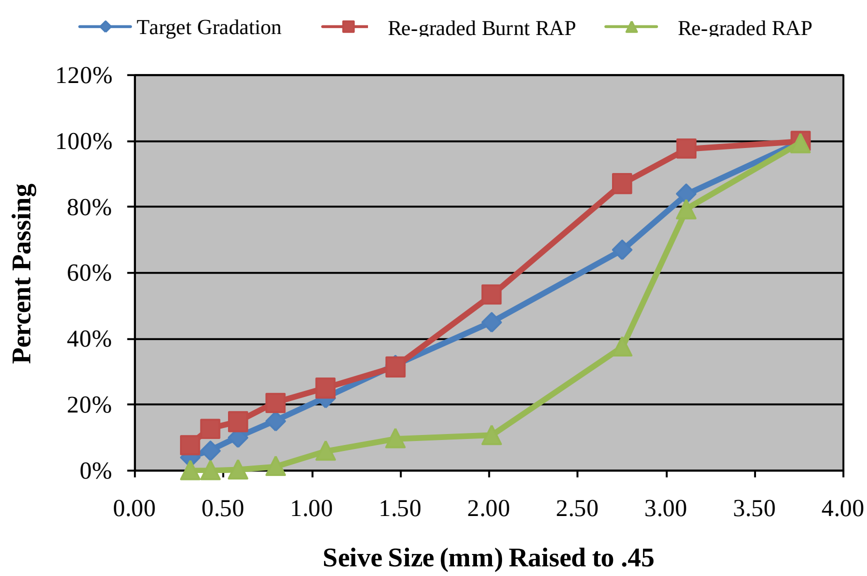


Figure 12: Re-gradation vs. Target Gradation

Using the re-gradation results, the RAP fractions were combined into batches for sample preparation. These samples were then run through the physical tests for this study, including dynamic modulus evaluation and tensile strength determination.

4.2 Volumetric Properties

Four samples for each mix (resulting in twelve samples total) were prepared for the physical tests in this study. The Bulk Specific Gravity (BSG) was determined for each specimen. A Theoretical Maximum Density (TMD) of 2.485 was determined for all mix variations. This TMD was decided based on the previous research observation that the additives do not affect the TMD of the mix.

The additives affect the workability of the mix, which in turn increases compactability of a mix with the same TMD as the mix without the aid of additives. The average and standard deviation of the bulk specific gravity of the different mixes are shown in Figure 13. Compared to the control mix, the mixes with Sasobit® and zeolite additives achieved higher bulk specific gravities. This was expected due to the probable increase in workability of the mixes with the WMA additives. Volumetric raw data are presented in Appendix 3: Volumetric Mix Design Data

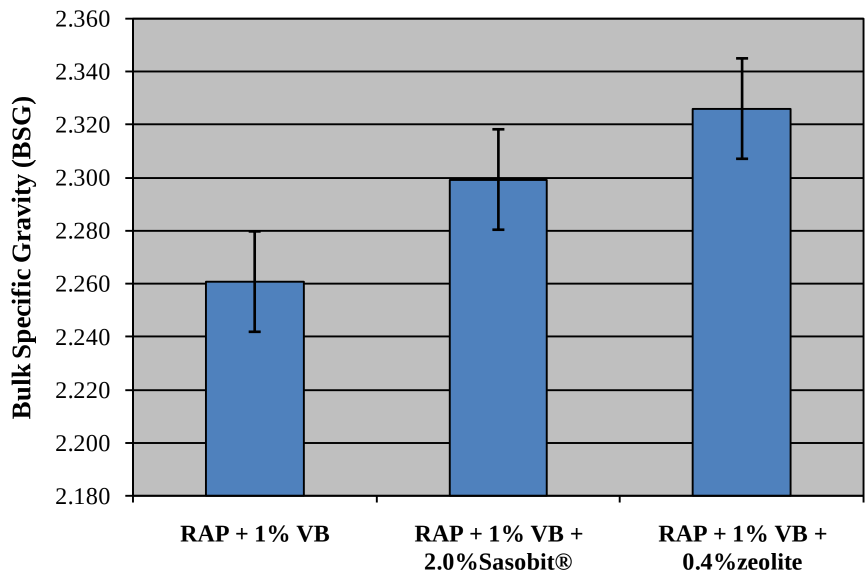


Figure 13: Average Bulk Specific Gravity of Different Mixes

The Percent Air Voids was determined for each sample using the BSG and TMD results. The average and standard deviation of the Air Void results are shown in Figure 14. Compared to the control mix, the mixes with Sasobit® and zeolite additive achieved lower air voids, as expected from the BSG results.

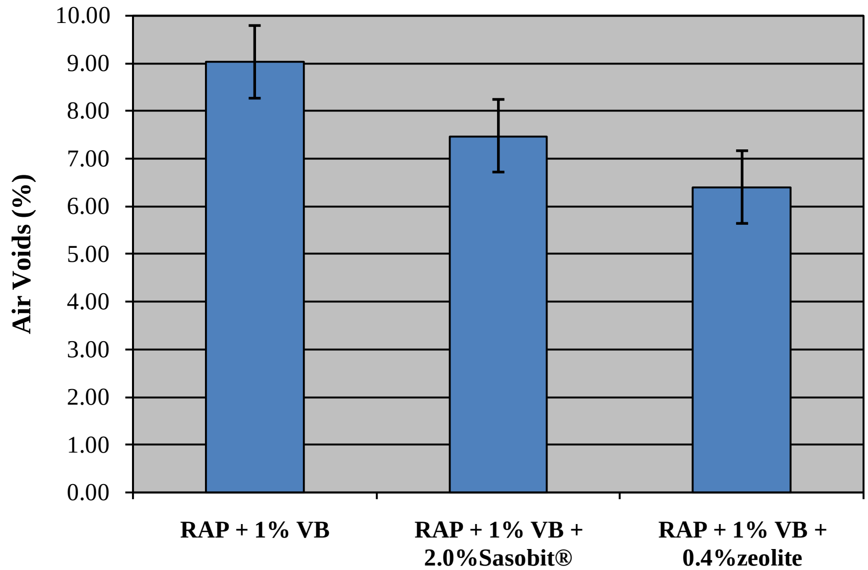


Figure 14: Percent Air Voids of Different Mixes

The decrease in air voids of the mixes using the WMA additives demonstrates the additives' abilities to increase the workability of the aged binder in the RAP.

4.3 Contact Angles

Comparing the contact angles between water and virgin asphalt binder to the contact angles with aged RAP binder provides a new analysis for asphalt. All aspects of the analysis, including the extraction process and its effect on the RAP binder and the comparison of contact angles with and without additives, were included.

4.3.1 Extraction and Slide Preparation

When compared with previous research using 100% virgin binder, the slides containing reclaimed asphalt were not as homogenous, even when Sasobit® or zeolite were added, as those prepared with virgin asphalt binder. Figure 15 shows a slide prepared with virgin binder and 2.0% Sasobit®.

Figure 15: 100% Virgin Binder

The asphalt extracted from the RAP coated the slides, but was much thinner in some areas and appeared to have veins, illustrated in Figure 16 and Figure 17.

Figure 16: RAP Asphalt + 1.0% VB + 2.0% Sasobit®

Figure 17: RAP Asphalt + 1.0% VB + 0.4% zeolite

The slides also attracted more dust than the 100% virgin binder slides. Factors that may have contributed include being stored outside of a fume hood and the altered nature of the RAP. If the RAP slides were less homogenous or tackier than virgin binder slides, they may have attracted more dust.

4.3.2 Contact Angle Analysis

Contact angles were measured using a goniometer and DROPimage Standard software. The average contact angle from each slide was determined by taking an average of the left and right angle readings. Both were considered good measurements because, theoretically, the contact angle should be the same on either side of the liquid drop. If one angle was incorrectly represented, and it was clearly visible that the DROPimage Standard software was taking an incorrect measurement, the angle measurement was discarded and not included in the analysis.

Average contact angle measurements are represented on Figure 18. Contact angles without aged binder had average angles that were much higher than slides with RAP aged binder. Higher contact angles mean the surface is hydrophobic. This is preferable in the pavement industry because asphalt pavements come in contact with rain, snow, sleet, and etcetera.

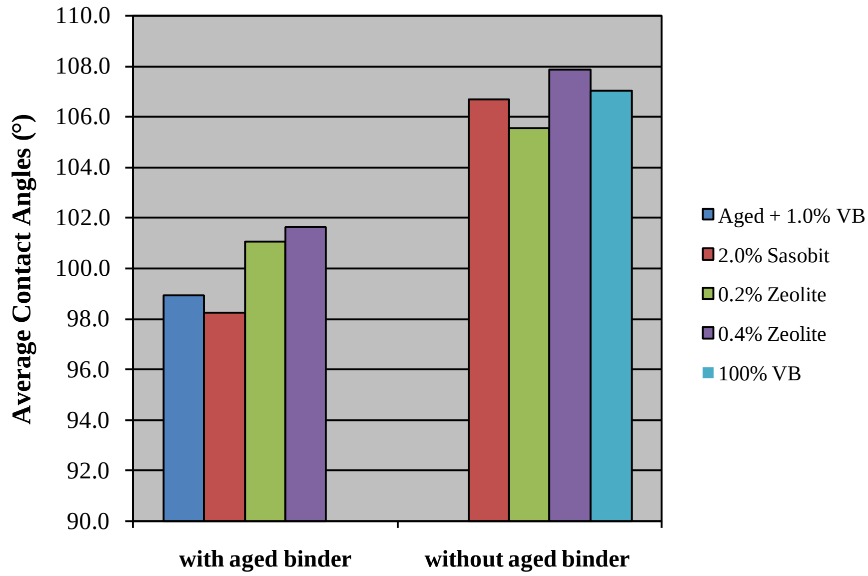


Figure 18: Effect of RAP and Additives on Average Contact Angles

The average contact angles, standard deviation and confidence levels of all of the slides are presented in Table 9. Higher standard deviations are present for slides with aged binder and slides with zeolite. In the lab, the contact angles with the aged binder were significantly more difficult to get proper readings because of the way the slides were coated. It was not desirable to have droplets on asphalt veins or on dust particles attached to the slide. For slides with zeolite, the liquid would often spread out too quickly to take an accurate measurement of the initial contact angle. This was undesirable, not only because it resulted in a bad reading, but also because the number of accurate contact angles was significantly reduced for slides with zeolite. Confidence values indicate that there is a 95% confidence that the measured angle will be that close to the average. For instance, it can be said with 95% confidence that a contact angle on Slide 1 will be between 100.1 (100.2-0.0764) and 100.3 (100.2+0.0764).

Table 9: Contact Angle Analysis

Slide	Contents	Average Contact Angle	Standard Deviation	Confidence
1	Aged + 1.0% VB	100.2	4.87	0.0764
2	Aged + 2.0% Sasobit®	98.3	3.67	0.0543
3	Aged + 0.2% zeolite	101.1	4.89	0.0780
4	Aged + 0.4% zeolite	101.6	5.61	0.0571
6	VB + 2.0% Sasobit®	106.7	1.882	0.569
7	VB + 0.2% zeolite	105.6	1.805	0.495
8	VB + 0.4% zeolite	107.9	4.463	1.179
9	100%VB	107.0	2.690	1.014

An Analysis of Variance (ANOVA) was conducted for contact angles and several null hypotheses were tested. Table 10 shows the ANOVA tests that were conducted. The hypothesis for each of the ANOVA was that the treatments compared would be statistically insignificant. If the calculated F value will be greater than or equal to the critical F value, the null hypothesis can be rejected.

Table 10: ANOVA Treatments Compared

Comparison	Treatment Sets	
1	4 slides with Aged Binder(AB) + 1.0% Virgin Binder(VB)	
2	4 Slides with VB	
3	AB + 1.0% VB	100% VB
4	2.0% Sasobit®AB + 1.0% VB	100% VB
5	0.4% zeolite + AB + 1.0% VB	100% VB
6	2.0% Sasobit® + AB + 1.0%	AB + 1.0%VB
7	0.4% zeolite + AB + 1.0% VB	AB + 1.0%VB
8	2.0% Sasobit® + AB	2.0% Sasobit® VB
9	0.2% zeolite + AB	0.2% zeolite VB
10	0.4% zeolite + AB	0.4% zeolite VB

The treatments compared in the ANOVA are presented in Table 10. For the most part, there was no statistical difference between the contact angles. The reasoning behind the lack of a difference cannot be explicitly explained because it relies on several factors. For instance, when the ANOVA compared different additives to virgin binder and aged binder (Comparisons 3 through 7), there was no statistical difference for any of the scenarios. However, the aged binder may not have had sufficient time to mingle with the virgin binder. If this was the case, contact angles may alter over time. If there was sufficient time to mingle, there may actually be no significant difference between virgin binder and aged binder. The same situation occurred when comparing aged binder slides each other (Comparison 1) and virgin binder slides to each other (Comparison 2).

However, when an ANOVA was performed between the Sasobit® slides with and without aged binder (Comparison 8), the null hypothesis was rejected. This suggests that there may have been a significant difference and the virgin binder and aged binder had a change to mingle. This may happen with Sasobit® quicker than zeolite because of the different framework of the Sasobit® that allows the asphalt to flow easier. Sasobit® slides were also heated to 70°C during the slide preparation process to dissolve the wax, which may have assisted in the mingling of the aged and virgin binder. All contact angle ANOVA tables are presented in Appendix 4: Contact Angle ANOVA

4.4 Indirect Tensile Strength Test (ITS)

Indirect Tensile Strength was tested for three mixes at room temperature. Figure 19 presents the average indirect tensile strength values for each of the mixes. For each mix, three unconditioned and three conditioned specimens were tested. The indirect tensile strengths of the control and zeolite cores were impacted by the moisture conditioning (not very pronounced for the control samples). Alternatively, the Sasobit® samples seemed to improve with moisture conditioning. One of the zeolite samples had an unusually low tensile strength, which influenced the overall strength average. However, even with the outlier excluded from the results, the average strength is still much lower than Sasobit® and control samples.

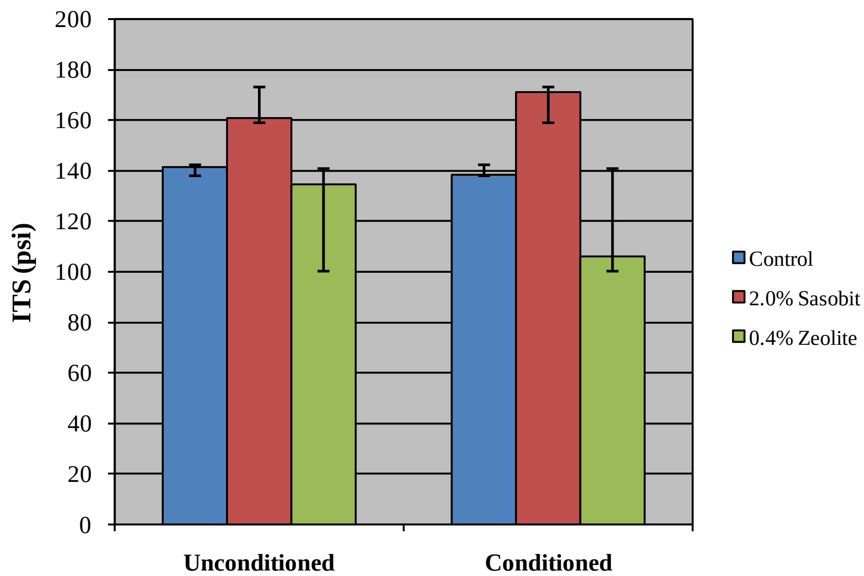


Figure 19: Indirect Tensile Strength

The tensile strength ratio (TSR) of moisture conditioned vs. unconditoned strength, shown in Figure 20, should be at least 80% for a mix with sustained tensile strength. The control and Sasobit® samples met the 80% and the zeolite ratio was just under 80% (78.9%). Air voids in the zeolite mix may have had a contribution to the low ratio and could have contributed to the lower ITS values observed.

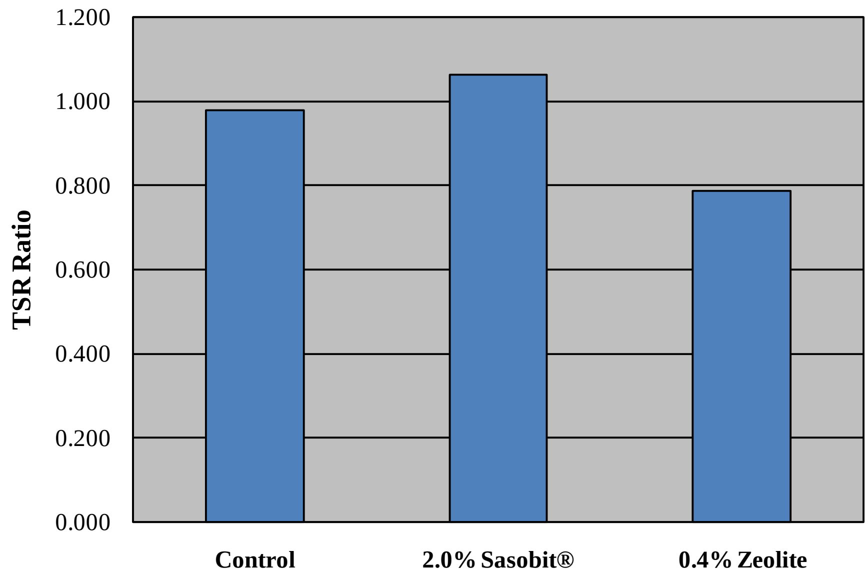


Figure 20: Indirect Tensile Strength Ratio: Conditioned vs. Unconditioned

During the accelerated moisture conditioning process the saturation (%) was determined. The saturation of the WMA additive aided mixes decreased compared to the control mix, this is representative of Figure 21: Saturation (%) of Different Mixes Figure 21. This was expected considering the volumetric results that showed decreased air voids were in the mixes with Sasobit® and zeolite. By visually inspecting results in Figure 20 and Figure 21, one can observe that there is no strong correlation between degree of saturation and TSR ratio. For instance, RAP with 1% VB plus 0.4% zeolite had the lowest degree of saturation but the lowest value of TSR ratio while the control mix had the highest degree of saturation but not the lowest TSR ratio.

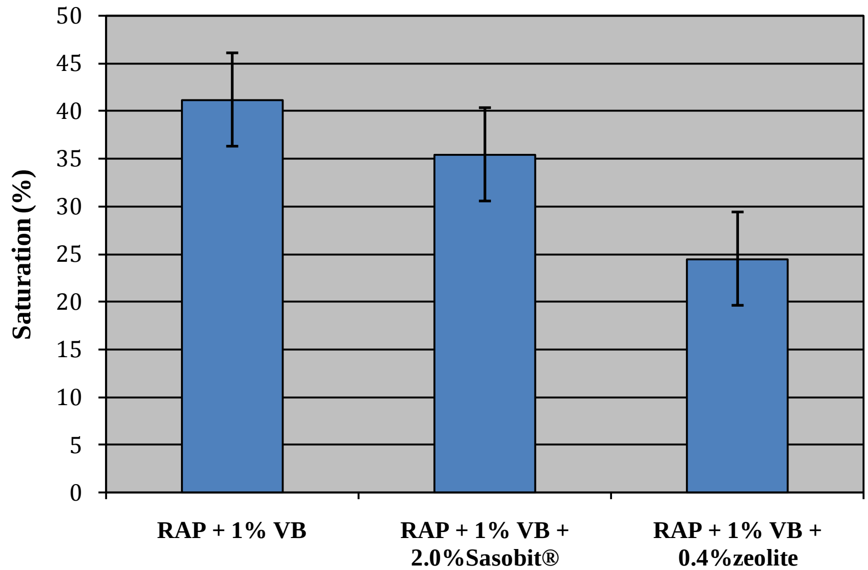


Figure 21: Saturation (%) of Different Mixes

4.5 Dynamic Modulus (|E*|)

The dynamic modulus (|E*|) of three mixes of interest was determined through mechanical testing and MATLab® aided interpretation. In order to determine the moisture susceptibility of the mixes, the samples were tested before and after an accelerated moisture conditioning process. The dynamic modulus and phase angle results for each sample at each temperature and frequency before and after moisture conditioning can be found in Appendix 5: Dynamic Modulus Raw Data

The |E*| ratio was calculated to compare the conditioned samples to the unconditioned samples at the same temperature. The control and zeolite mixes had lower dynamic moduli ratios at 10Hz than at 0.1Hz. Considering that temperature remained constant for each test, the decreased moduli were most likely due to the frequency of the load. Conversely, however, the ratio increased with an increase in frequency for Sasobit® samples.

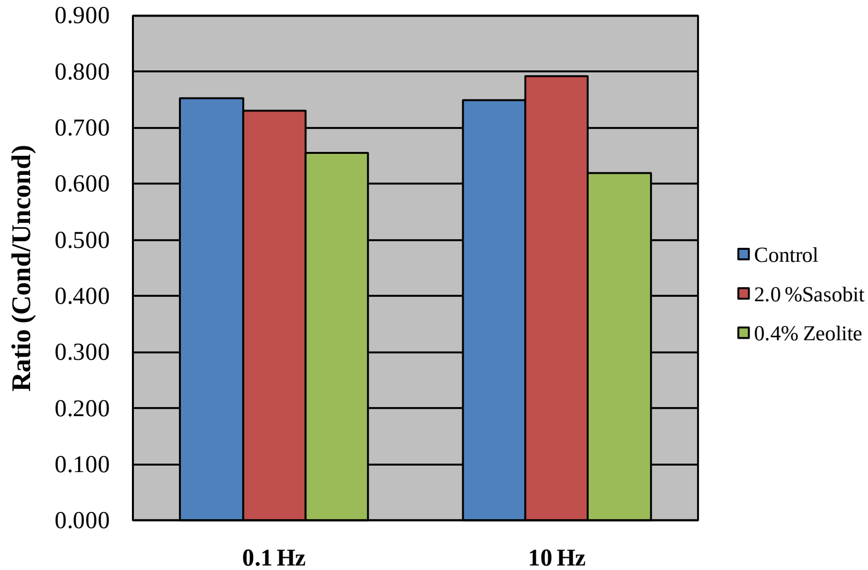


Figure 22: Dynamic Modulus Ratio at 37ºC

Figure 23 shows the dynamic moduli at varying temperatures under a frequency of 10Hz. As expected, increases in temperature resulted in reduced moduli. |E*| testing was important at varying temperatures because increased temperature is known to be a factor in permanent deformation such as rutting. Compared to the control mix, the mix aided by zeolite resulted in the least desirable |E*| performance. The Sasobit® aided mix showed the most desirable |E*| performance of the three mixes.

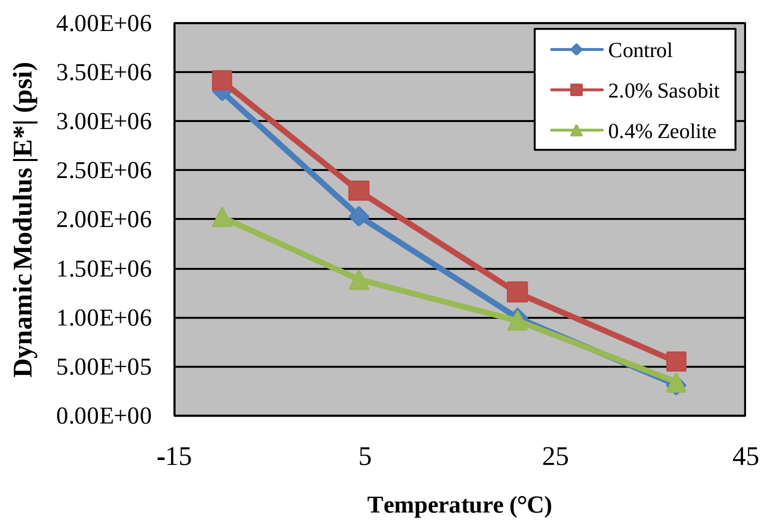


Figure 23: Uncondtioned Samples at 10 Hz

The plots, superimposed horizontally, in Figure 24 represent how the different unconditioned moduli from each mix compared to each other from varying frequencies and temperatures in the Universal Testing Machine. The |E*| of the unconditioned samples demonstrates that Sasobit® offers an increase in modulus over the control except at -10°C and 5 Hz mix and zeolite showed no improvement. The combination of increased temperature and decreased loading frequency showed a lower modulus for all three mixes, which was expected.

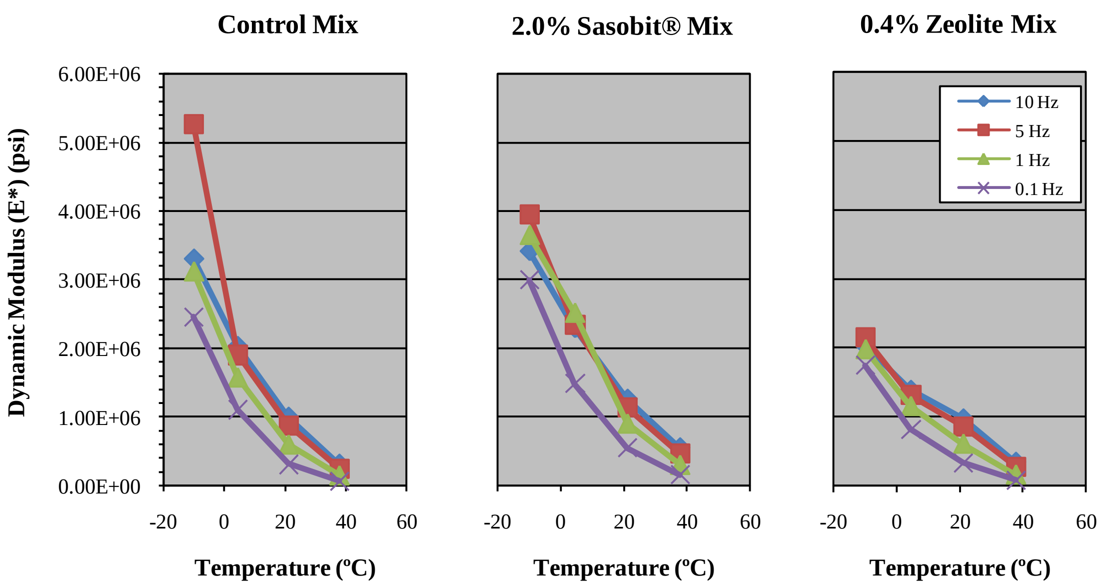


Figure 24: Dynamic Modulus vs. Temperature

The dynamic moduli ratio was compared to the TSR value and the percent saturation to determine if there was any correlation between the two physical tests. It appears from Figure 26 that there is a correlation between TSR and |E*| ratio based on limited testing data from this study.

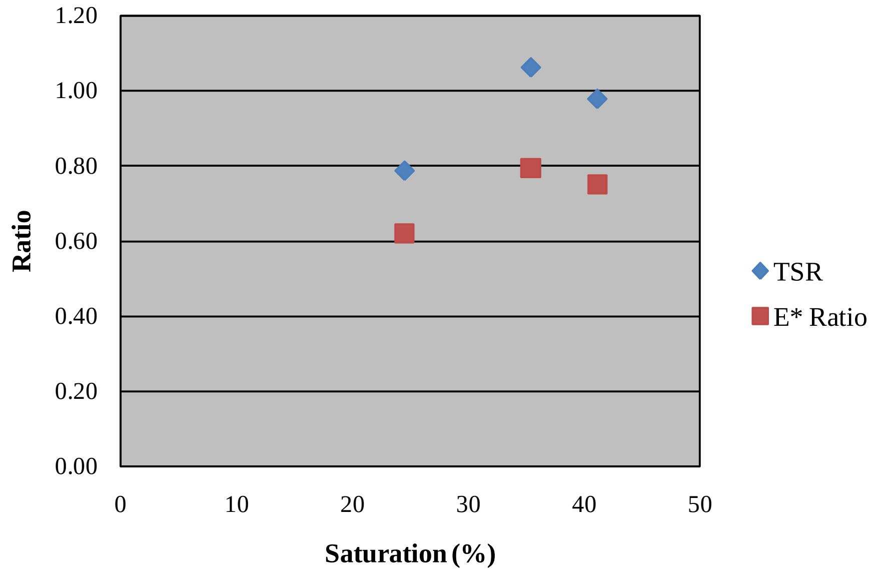


Figure 25: TSR and |E*| Ratios in relevance to Saturation

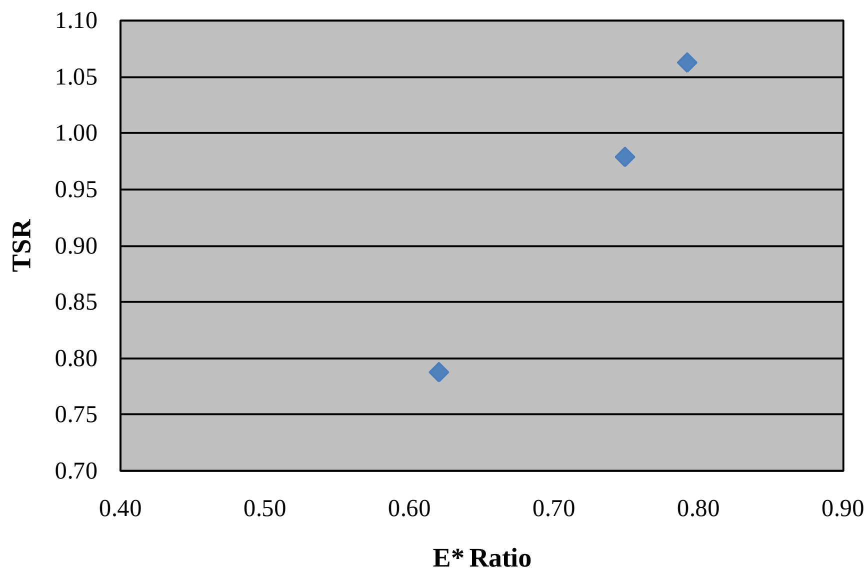


Figure 26: E* Ratio vs. TSR

An ANOVA was completed for dynamic modulus to determine if moisture conditioning had a significant effect on |E*| results at 37.8°C with varying frequencies. Figure 27 represents the loading frequency's effect on the dynamic modulus at 37.8°C.

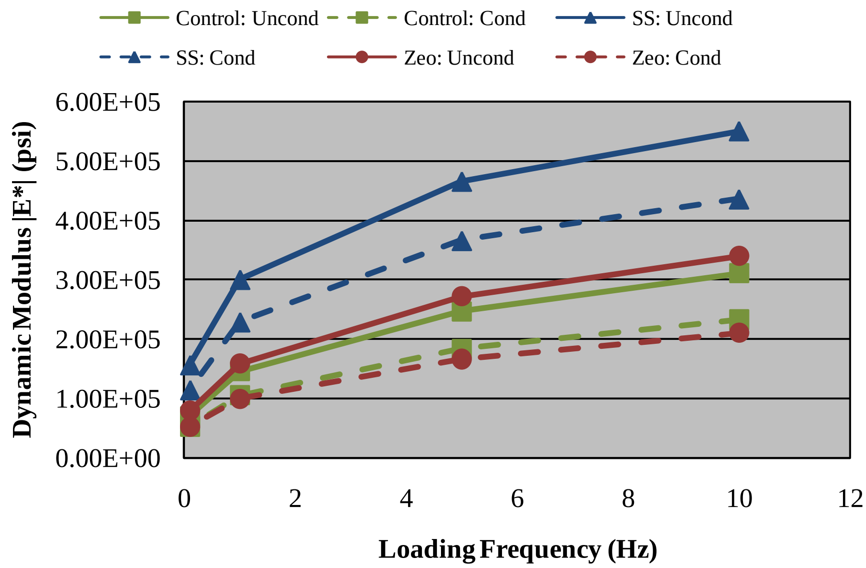


Figure 27: Dynamic Modulus of Unconditioned and Conditioned Samples at 37.8°C

The moisture conditioned control mix was significantly different from the unconditioned sample at 10Hz, but was not significant at 5Hz, 1Hz, or 0.1Hz. As shown on Figure 24, this may have been due to the outlier in the control mix at 5Hz. The Sasobit® aided specimens had no significant difference between unconditioned and conditioned samples. However, it is apparent that there is significant difference in dynamic modulus of the Sasobit® aided mix from Figure 27. Conversely, there was a significant difference between unconditioned and conditioned samples at all four frequencies for zeolite mixes. This phenomena with the zeolite samples could have occurred because of increased moisture susceptibility as illustrated in Figure 20 where it had a relatively low value of TSR. Zeolite is known as a foaming additive and there has been some concern that it increases the moisture in samples. This may have been the case for these samples. All E* ANOVA tables are attached in Appendix 6: |E*| ANOVA Tables

The |E*| results imply that the Sasobit® aided mix produces the most desirable of the three mixes of interest when using 100% RAP. Compared to the control mix, the zeolite aided mix showed no improvement of modulus and was more impacted by moisture conditioning.

4.6 Cost Comparison

A cost comparison was completed for RAP mix designs used in this study and an HMA mix with no additives. The virgin binder content, amount and type of additives used, and oven temperature were all taken into account to produce a price per ton of each mix. Cost analysis is presented in Table 11 through Table 15 with a summary in Table 16, presented in Table 16.

Table 11: Cost of 100% RAP Mix with 6% VB & 2.0% Sasobit® at 130°C

Component	Amount	Price/ton	Cost
100% RAP	1 ton	$5.00	$5.00
Energy (130°C)		$0.74	$0.74
Virgin Binder	6% of mix	$800.00	$48.00
Sasobit®	2.0% of VB	$3000.00	$3.60
TOTAL			$57.34

Table 12: Cost of 100% RAP with 1% VB & 2.0% Sasobit® at 130°C

Component	Amount	Price/ton	Cost
100% RAP	1 ton	$5.00	$5.00
Energy (130°C)		$0.74	$0.74
Virgin Binder	1% of mix	$800.00	$8.00
Sasobit®	2.0% of VB	$3000.00	$3.60
TOTAL			$14.34

Table 13: Cost of 100% RAP with 6% VB & 0.4% zeolite at 130°C

Component	Amount	Price/ton	Cost
100% RAP	1 ton	$5.00	$5.00
Energy (130°C)		$0.74	$0.74
Virgin Binder	6% of mix	$800.00	$48.00
Zeolite	0.4% of mix	$0.00024	$0.24
TOTAL			$53.98

Table 14: Cost of 100% RAP with 1% VB & 0.4% zeolite at 130°C

Component	Amount	Price/ton	Cost
100% RAP	1 ton	$5.00	$5.00
Energy (130°C)		$0.74	$0.74
Virgin Binder	1% of mix	$800.00	$8.00
Zeolite	0.4% of mix	$0.00024	$0.04
TOTAL			$13.74

Table 15: Cost of HMA

Component	Cost/ton
HMA	$80.00
Energy (150°C)	$0.94
TOTAL	$80.96

Table 16: Cost Comparison of Mixes

Mix	Cost
100% RAP with 6.0% VB & 2.0% ® at 130°C	$57.34
100% RAP with 1.0% VB & 2.0% Sasobit® at 130°C	$14.34
100% RAP with 6.0% VB & 0.4% zeolite at 130°C	$53.98
100% RAP with 1.0% VB & 0.4% zeolite at 130°C	$13.74
HMA at 150°C	$80.96

The RAP used in this study was donated, but a milling and trucking cost has been added because it will generally be a cost associated with RAP technologies. Costs will vary with each contractor, but this comparison estimated $5.00 per ton for milling and trucking in the field (Kristjansdottir, Muench, Michael, & Burke, 2007). Sasobit® and Advera® Zeolite costs were obtained through personal communications with company representatives and cost $1.50 per pound ($3000/ton) and $0.50 per pound ($1000/ton), respectively. Energy cost estimates were determined to be $0.74 per ton at 130°C and $0.94 per ton at 150°C, based on fuel costs (Keeches & LeBlanc, 2007).

As seen in Table 16, reducing the virgin binder from 6.0% to 1.0% by mass greatly reduces the cost per ton of pavement. Virgin binder is expensive and if it is possible to reduce the amount of binder by using RAP and additives, the possibility should be explored. The cost of a 100% RAP mix with 2.0% Sasobit® was reduced by $43 with the reduction of virgin binder from 6.0% to 1.0%. A similar effect occurred with zeolite and the price was reduced by approximately $40. Sasobit® and Advera® Zeolite are approximately the same price per ton when less virgin binder is used.

When compared with hot mix asphalt, Sasobit® and Advera® Zeolite are 30% to 40% cheaper per ton, even with a higher percentage of virgin binder. When that binder is reduced to 1.0%, RAP mixes with additives cost approximately 83% less than HMA.

4.7 Environmental Analysis

Environmental considerations are the basis of the long term goal of this study. In order to develop sustainable design procedures, the environmental impacts and the use of virgin materials must be carefully assessed. The ultimate goal is to produce the most durable pavement with 100% recycled materials. In this research, environmental factors were directly addressed by reducing the amount of virgin materials used. The mix designs were completely comprised of reclaimed pavement and 1.0% by mass virgin asphalt binder.

WMA additives that increase workability at reduced temperatures. Keeches et al. discovered that there is a 16% heat energy reduction when heating an oven from ambient temperatures (25℃) to 130℃ as compared to 150℃. This is an essential finding addressing the reduction of carbon dioxide (CO_2) emissions due to oven temperatures. They also found that there was a 27.9% reduction in CO_2 emissions when reducing the temperatures from conventional HMA temperatures of 150℃ to 130℃ with1.0% Sasobit®. Thus, the total CO_2 emissions reduction was 43.9%. The reduction of temperatures also reduces the fuel consumption required to heat the mix during mixing as well as during transport to the paving site. Reducing the fuel required will also reduce the CO_2 emissions.

Based on the research of Keeches et al., the total energy and CO_2 reduction of this study due to temperature reduction was determined and presented in Table 17.

Table 17: Energy & CO_2 Reduction

Temperature	Energy(J)	CO_2 (ppm)
150°C	125	716.67
130°C	105	516.67
Reduction	16%	43.9%

Even with these promising CO_2 reductions, the longevity of WMA with additives should be assessed to ensure that the mixes are comparable to HMA. A 100% RAP mix also reduces the amount of virgin materials required in production. Reducing the amount of new aggregates by using reclaimed materials provides a sustainable way to reuse and recycle old material. RAP also requires less virgin asphalt binder than conventional HMA or WMA with all virgin materials because it already has some aged binder included. However, even if the initial emissions are reduced, a warm mix with a shorter lifespan will require more field work and pavements. This will result in an overall increase in emissions, which is undesirable in sustainable development.

5 Conclusions

Advera® Zeolite and Sasobit® have an effect on WMA moisture susceptibility and several conclusions and recommendations have arisen. Even though the reduction of temperature has proven to be effective in the lab, plant conditions may vary. Before converting a plant to WMA, the plant should be evaluated to ensure that the reductions in oven temperatures are feasible on the existing equipment.

5.1 Asphalt Binder Contact Angle Tests

Contact angles are influenced by additives when using virgin binder at warm mix temperatures. This type of analysis is new to the asphalt industry and no asphalt binder slide preparation specification was used in this study. With the process used, slides were not uniformly coated with extracted RAP asphalt binder and these contact angles were slightly lower than slides with no extracted RAP. This was probably a result of aging the binder during the extraction process. No significant difference was found between contact angles when aged binder was used, but the difference may be due to impacts from the extraction process of asphalt binder from the RAP. New extraction procedures should be investigated that limit the factors attributing to the roughness of slides coated with aged asphalt binders.

After the 10-day waiting period, the slides had dust and other particles stuck to them, which made contact angle analysis difficult. If these procedures are repeated, slides should be stored in an airtight container under a hood to reduce the amount of dust accumulated. One downside of using a software program to determine contact angles is that sometimes it had difficulties distinguish between the surface and dust or other particles on the slide. Similarly, the slides are easily scratched and binder can be rubbed off easily, so handling should be limited to preserve the integrity of the slides.

More research should be completed comparing contact angles of extracted aged binder to 100% virgin binder. Also, other liquids with known properties, such as diiodomethane and formamide, should be investigated.

5.2 Mix Tests

Overall the physical test results suggest that WMA additives Sasobit® and Advera® Zeolite are successful in improving the physical properties of a 100% RAP mix design. Advera® Zeolite showed a better improvement in volumetric properties, however |E*| and strength were improved more by the aid of Sasobit®. This could be due to the levels of additive used and therefore, further research should be conducted to determine the optimum levels of WMA additives. Also, humidity influenced the initial sieve analysis and caused fewer fine aggregates to pass the 300 sieve. If humidity can be controlled, it should be monitored and reduced to avoid this issue.

5.2.1 Volumetric Properties

The WMA additive aided mixes showed an apparent improvement in volumetric properties. An increase in BSG resulted in a decrease in air voids, which confirms that the WMA additives increased the workability of the mixes. Increased workability permits a lower than conventional compaction temperature. The results from this study are promising; however, only three mixes were researched. As such, more research should be conducted to determine the ideal levels of additives for a 100% RAP mix design.

5.2.2 Dynamic Modulus

For all three mixes there was an apparent trend in relation to temperature and loading frequency, as the testing temperature increased and the loading frequency decreased, the |E*| decreased. A higher |E*| is desirable to resist permanent deformation such as rutting, making the Sasobit® aided mix the most desirable of the three mixes in this respect. The Advera® Zeolite aided mix, however, showed no improvement in |E*| when compared to the control mix. In order to validate the results of this study, which considered a limited sample size of limited mix variations, more testing should be completed. Expected conclusions were made for the Sasobit® aided mix design. The Advera® Zeolite mix design did not show significant improvement over the control mix. This could be due to the level of Advera® Zeolite in the mix, so different levels should be considered for further research.

At a high temperature (37.8°C) and a moderate loading frequency (10 Hz) the performance of the Sasobit® aided specimens showed notably better performance over the control mix when considering the ratio of the unconditioned and the conditioned moduli. Considering a desired ratio of 0.80, the Sasobit® aided mix was the only mix with close to satisfactory performance. The zeolite aided mix showed a decrease in performance over the control. This would suggest prominent moisture damage to the mixes without Sasobit® from the moisture conditioning.

5.2.3 ITS

Both the control and WMA modified mixes had high TSR values, suggesting significant tensile strength sustained after moisture conditioning. To investigate the possibility of thermal cracking, more research should be completed that tests the tensile strength at lower temperatures. Additionally, the Sasobit® aided mix had an increase in tensile strength over the control mix, which may be due to the formation of lattice structure. Overall, Advera® Zeolite had the poorest performance of the three mixes. This could be due to inconsistency in air voids and therefore suggests more testing should be completed.

This research was completed in a relatively short period of time. Continued research should be completed to compare the effects of Sasol Wax Sasobit® to Advera® Zeolite on moisture susceptibility of warm mix asphalt with RAP. Dynamic modulus ratios and tensile strength ratios of moisture conditioned and unconditioned mixes should be compared with more data to determine if there is actually a correlation between |E*| and TSR. Contact angles should also be investigated in more detail with different probe liquids and differing amounts of additives to determine if aged binder has any effect on wettability.

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Appendices

Appendix 1: LVDT Sample Mounting for Dynamic Modulus Testing

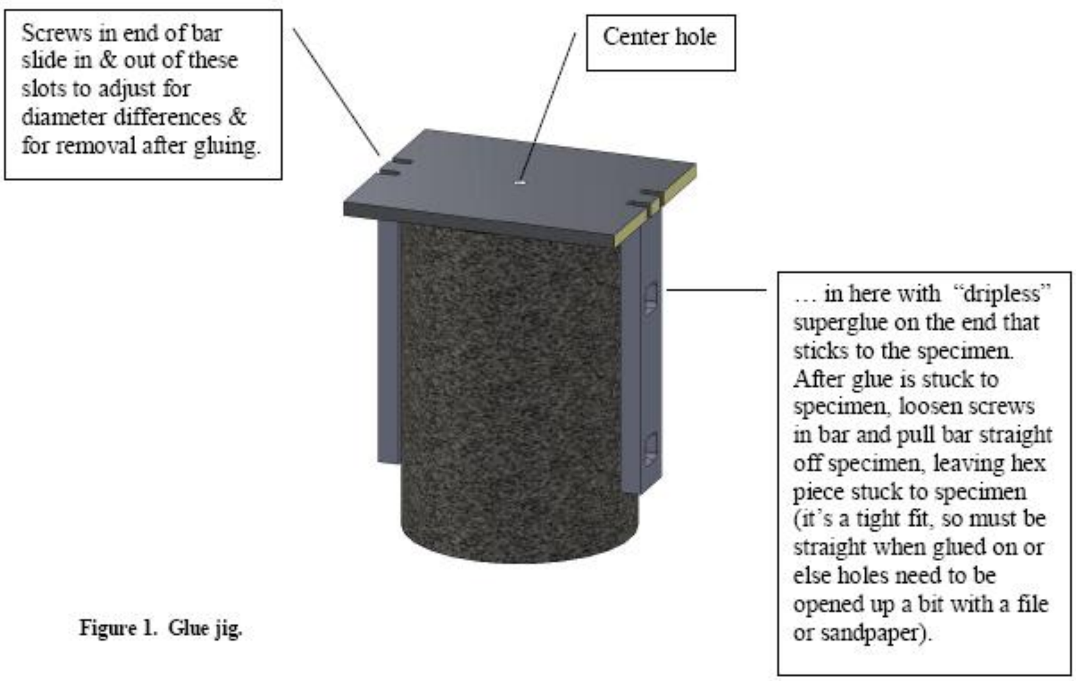


Figure 1. Glue jig.

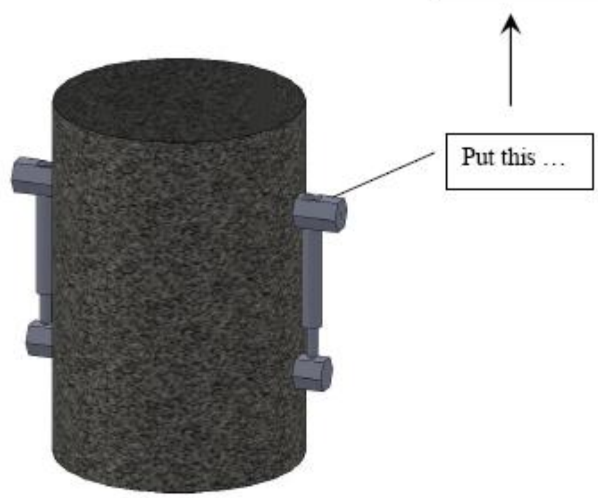
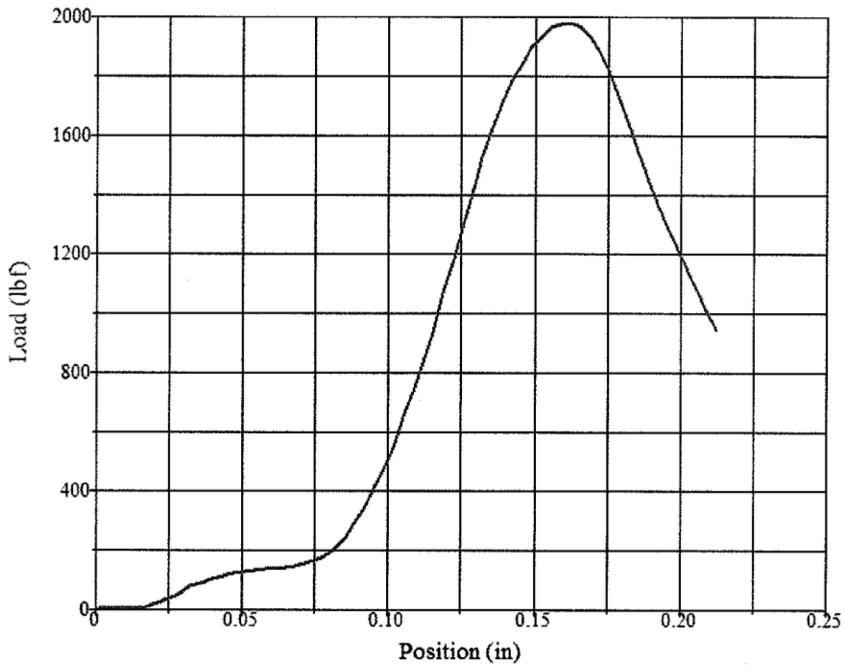


Figure 2. Instrumentation mount after gluing on hex pieces. LVDT can go up or down, depending on preference (dynamics vs gravity).

Appendix 2: Indirect Tensile Strength Shedworks® Output

CEINSTRON1132 10:43:59 AM 2/13/2009



Test Summary

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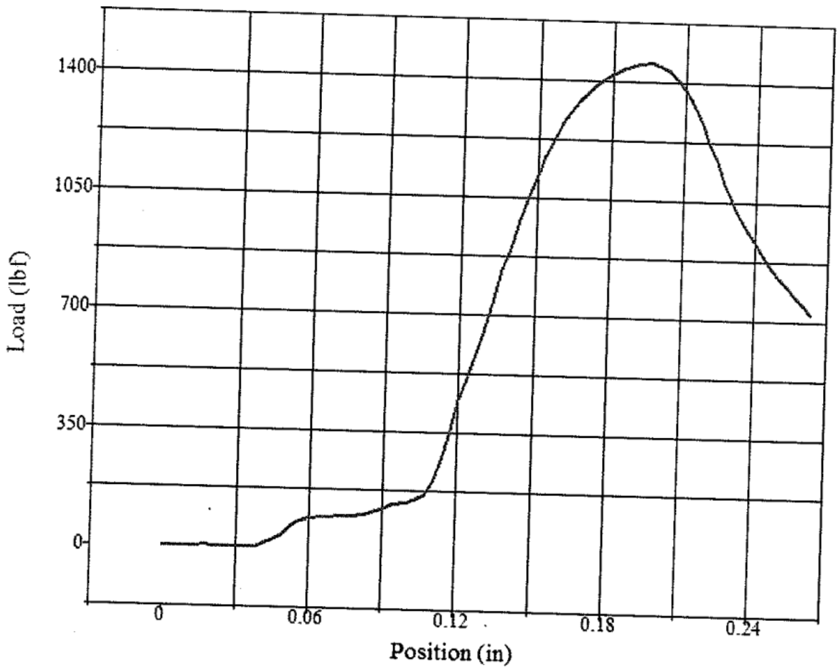
Start Time:	10:43:42 AM
End Date:	2/13/2009
End Time:	10:43:48 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1978 lbf

CEINSTRON1133

10:46:56 AM 2/13/2009



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Start Time:	10:46:42 AM
End Date:	2/13/2009
End Time:	10:46:50 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in^2
Peak Load:	1451 lbf

CEINSTRON1134

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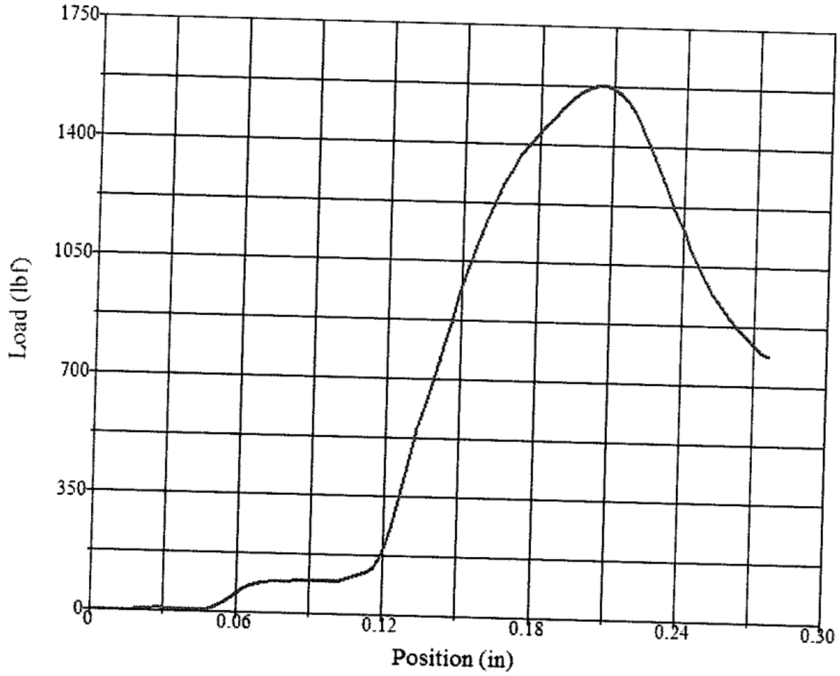

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Test Results

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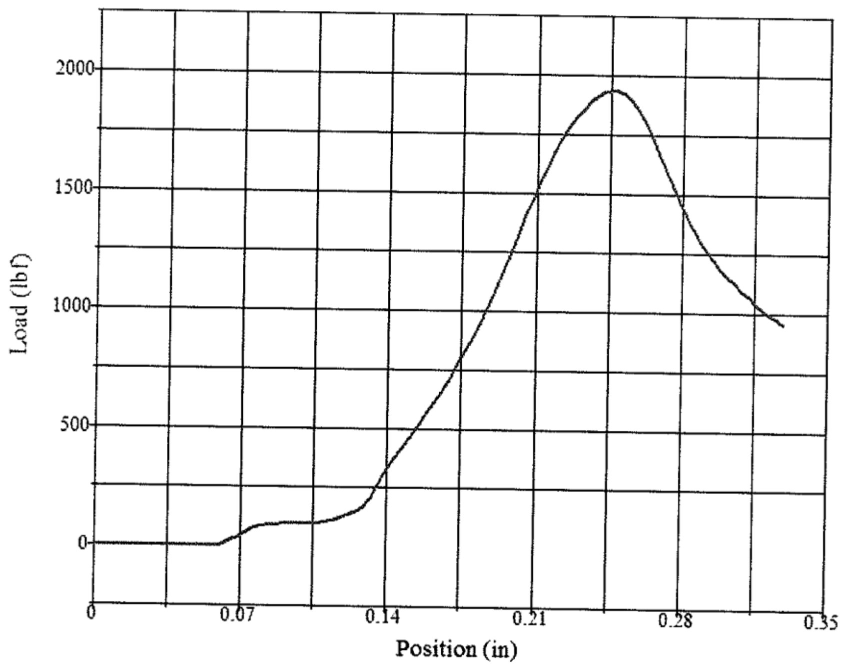
Area:	12.5664 in^2
Peak Load:	1576 lbf



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Tested By:	default

Test Results

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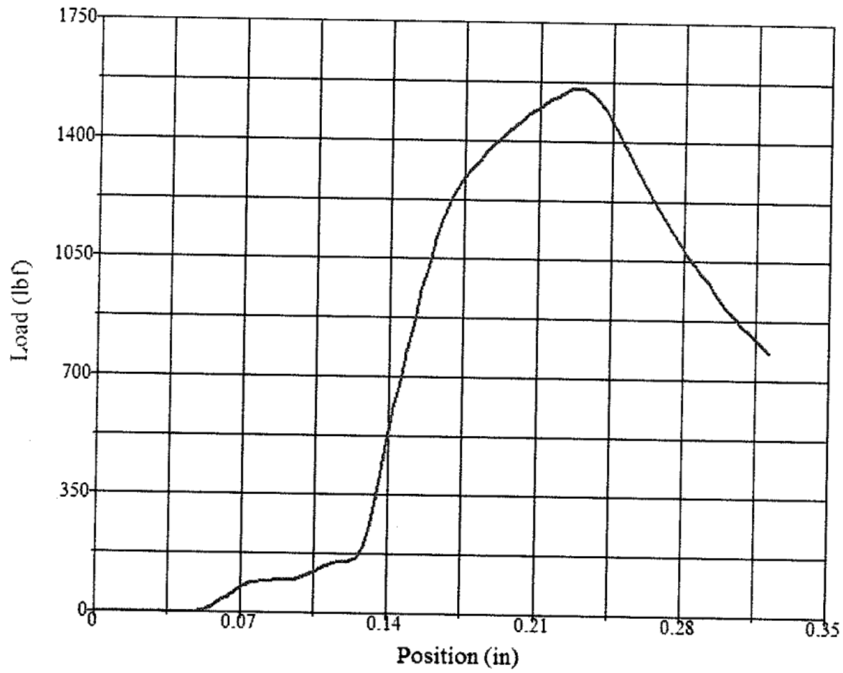
Area:	12.5664 in²
Peak Load:	1934 lbf



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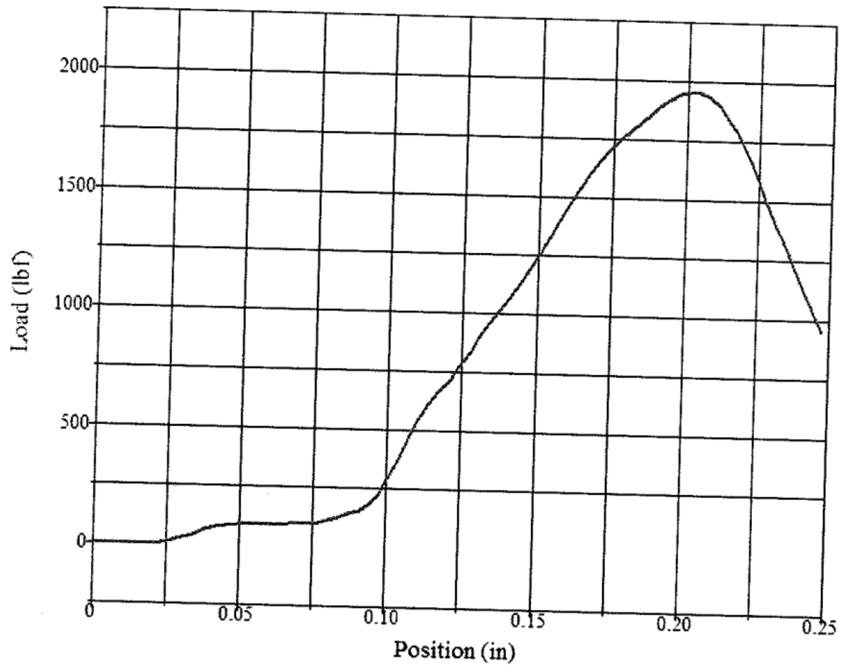
Elapsed Time:	00:00:09
Specimen Identification:	8-2
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/13/2009
Start Time:	10:59:39 AM
End Date:	2/13/2009
End Time:	10:59:48 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in^2
Peak Load:	1555 lbf

CEINSTRON1137

11:02:44 AM 2/13/2009

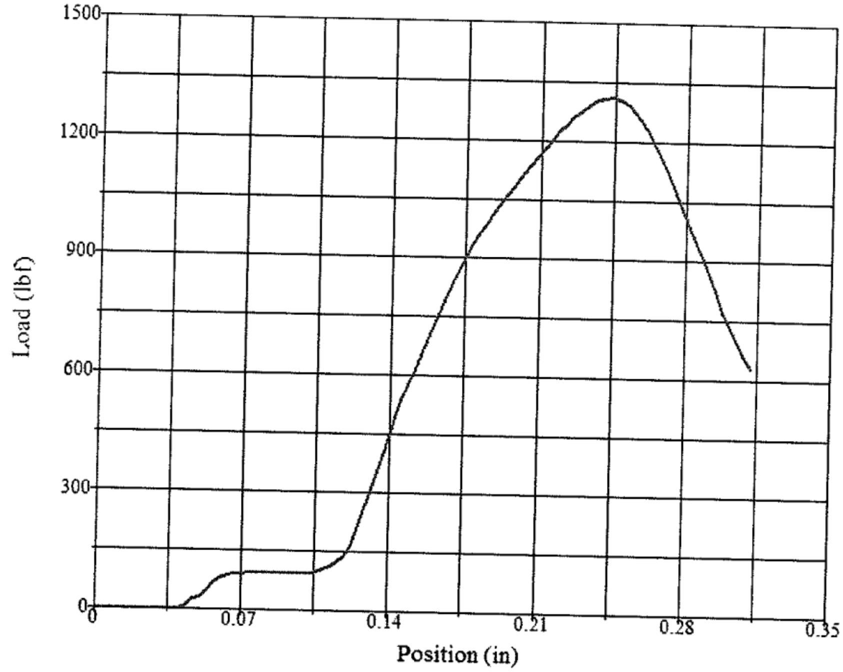


Test Summary

Counter:	137
Elapsed Time:	00:00:07
Specimen Identification:	8-3
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/13/2009
Start Time:	11:02:15 AM
End Date:	2/13/2009
End Time:	11:02:22 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1953 lbf



Test Summary

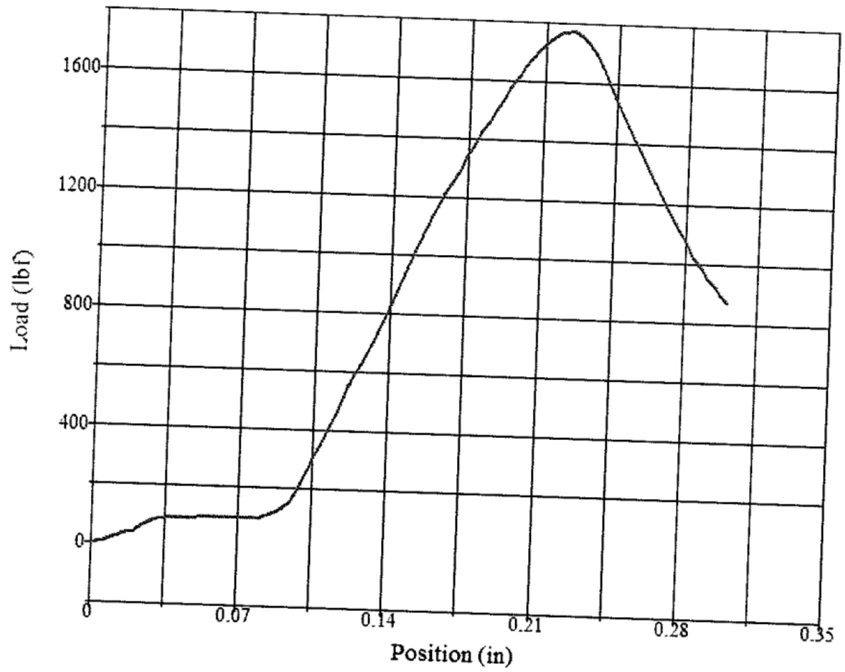
Counter:	138
Elapsed Time:	00:00:09
Specimen Identification:	12-1
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/13/2009
Start Time:	11:05:34 AM
End Date:	2/13/2009
End Time:	11:05:43 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1309 lbf

CEINSTRON1139

11:07:41 AM 2/13/2009

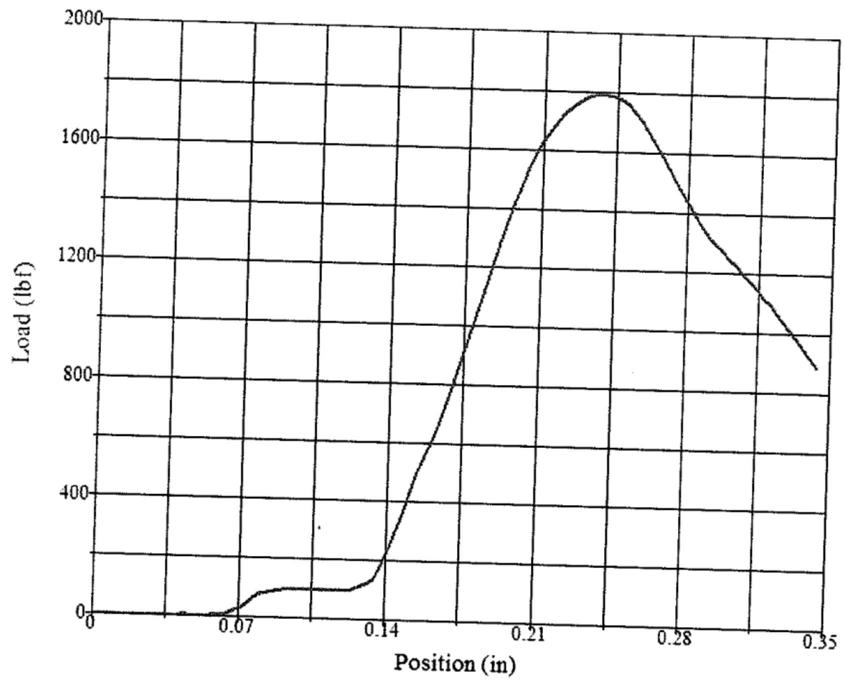


Test Summary

Counter:	139
Elapsed Time:	00:00:10
Specimen Identification:	12-2
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/13/2009
Start Time:	11:07:23 AM
End Date:	2/13/2009
End Time:	11:07:33 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in^2
Peak Load:	1771 lbf



Test Summary

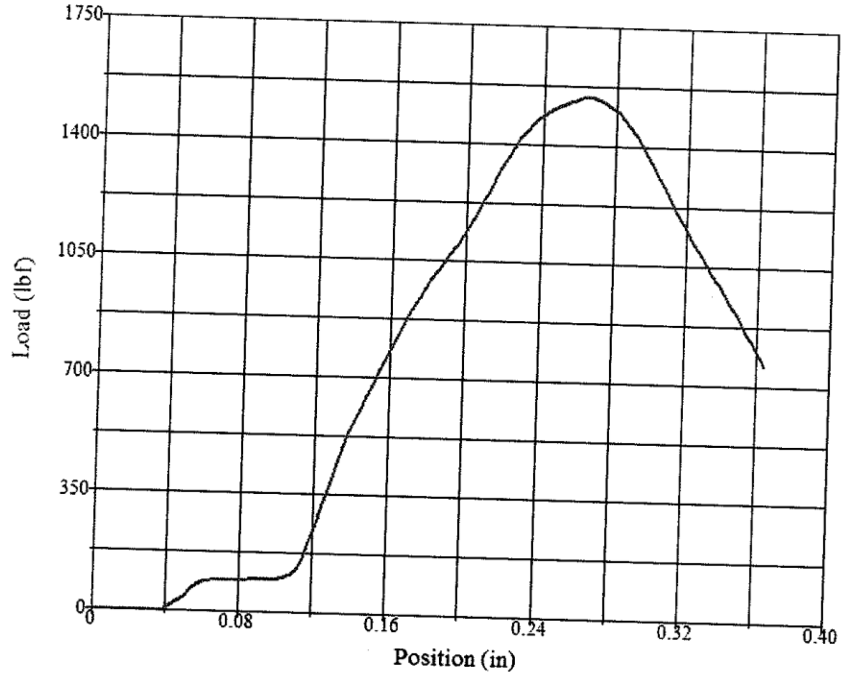
Counter:	140
Elapsed Time:	00:00:10
Specimen Identification:	12-3
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/13/2009
Start Time:	11:09:13 AM
End Date:	2/13/2009
End Time:	11:09:23 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1790 lbf

CEINSTRON1141

10:32:35 AM 2/16/2009



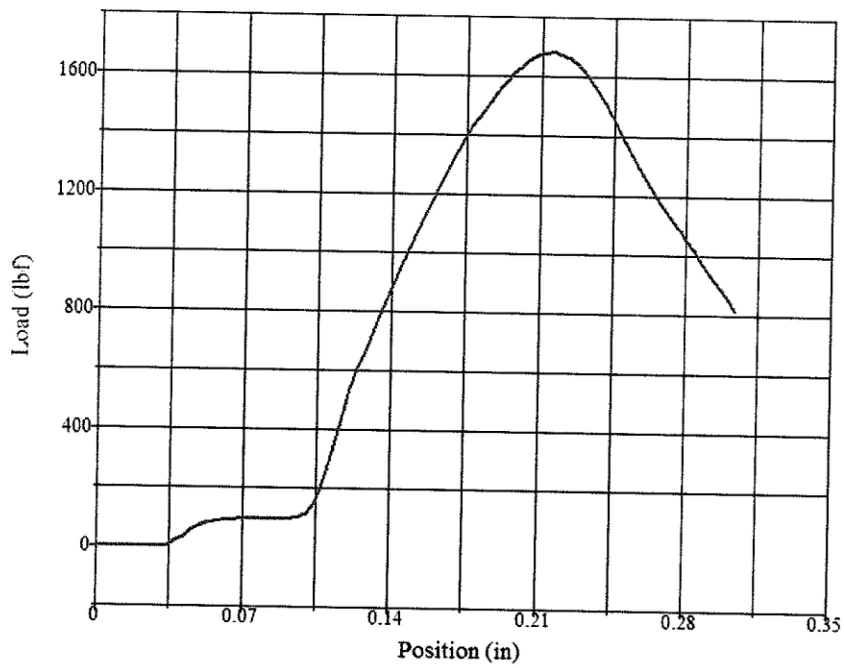
Test Summary

Counter:	141
Elapsed Time:	00:00:11
Specimen Identification:	3-1
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:31:47 AM
End Date:	2/16/2009
End Time:	10:31:58 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

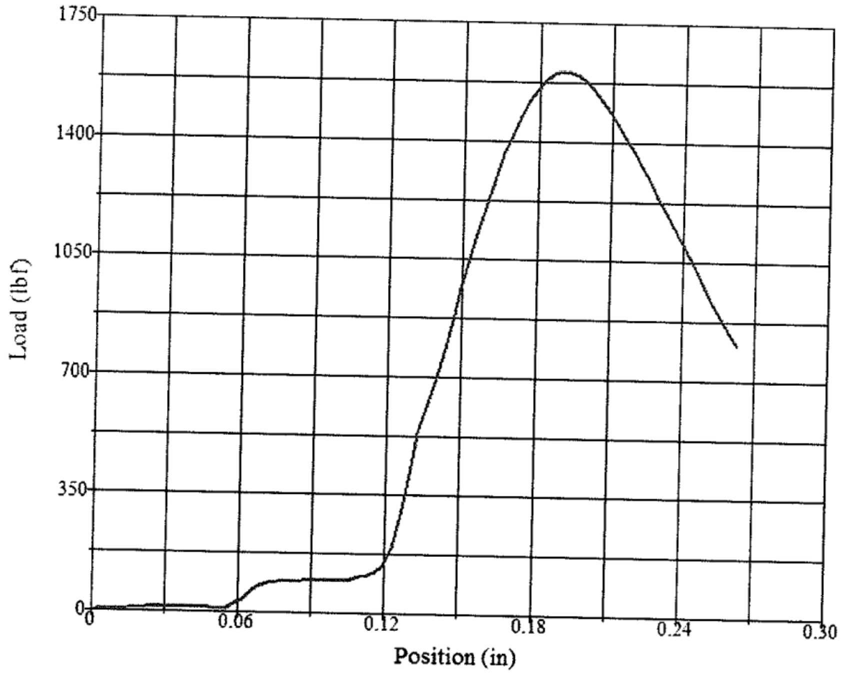
Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1541 lbf

*initially loaded 70 lbs



Test Summary	
Counter:	142
Elapsed Time:	00:00:09
Specimen Identification:	3-2
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:36:13 AM
End Date:	2/16/2009
End Time:	10:36:22 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results	
Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1678 lbf



Test Summary

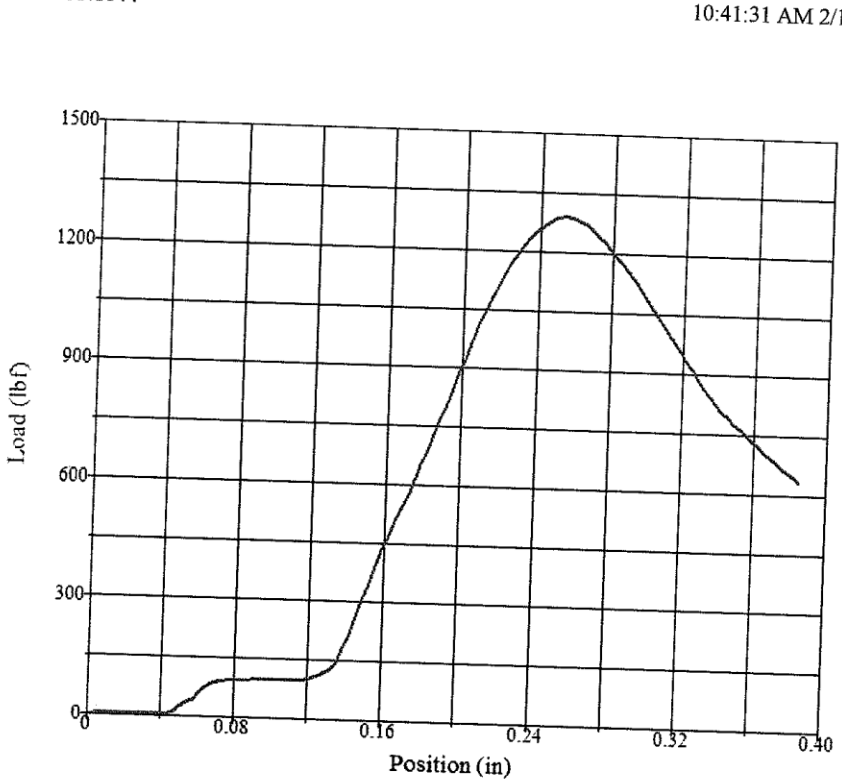
Counter:	143
Elapsed Time:	00:00:08
Specimen Identification:	3-3
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:39:17 AM
End Date:	2/16/2009
End Time:	10:39:25 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1605 lbf

CEINSTRON1144

10:41:31 AM 2/16/2009



Test Summary

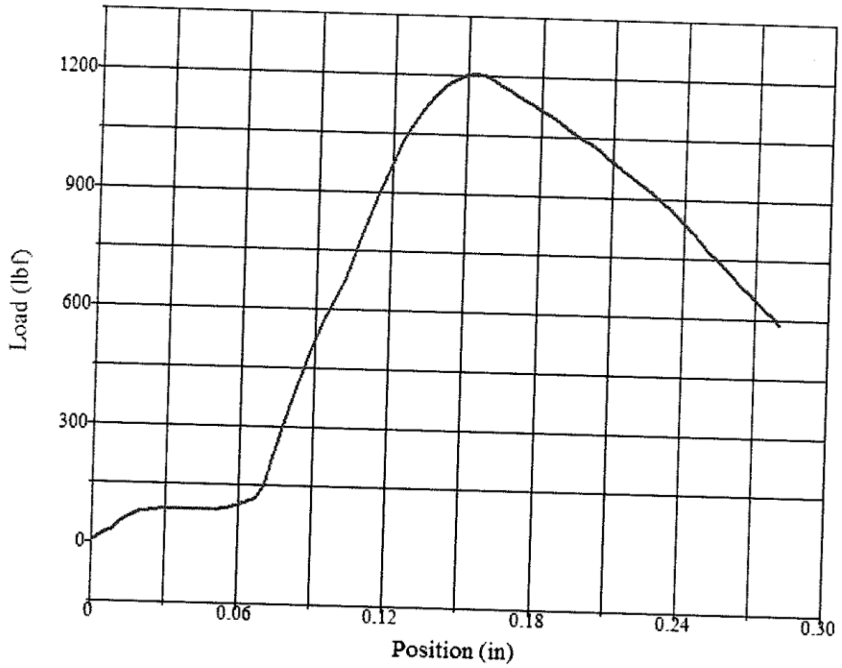
Counter:	144
Elapsed Time:	00:00:11
Specimen Identification:	9-1
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:41:13 AM
End Date:	2/16/2009
End Time:	10:41:24 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1288 lbf

CEINSTRON1145

10:44:03 AM 2/16/2009



Test Summary

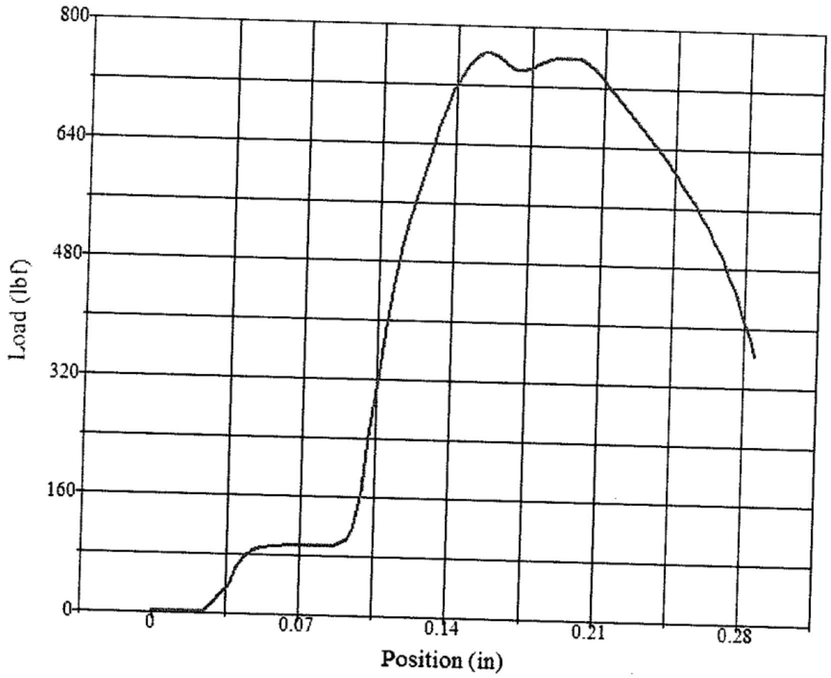
Counter:	145
Elapsed Time:	00:00:09
Specimen Identification:	9-2
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:43:21 AM
End Date:	2/16/2009
End Time:	10:43:30 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in^2
Peak Load:	1204 lbf

CEINSTRON1146

10:45:43 AM 2/16/2009



Test Summary

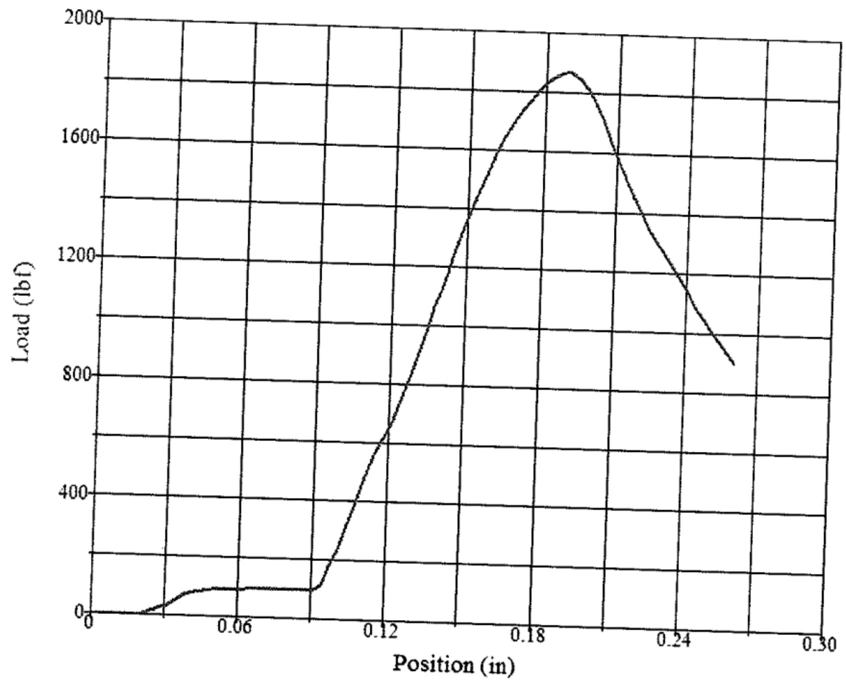
Counter:	146
Elapsed Time:	00:00:09
Specimen Identification:	9-3
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:45:26 AM
End Date:	2/16/2009
End Time:	10:45:35 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	763 lbf

CEINSTRON1147

10:47:46 AM 2/16/2009



Test Summary

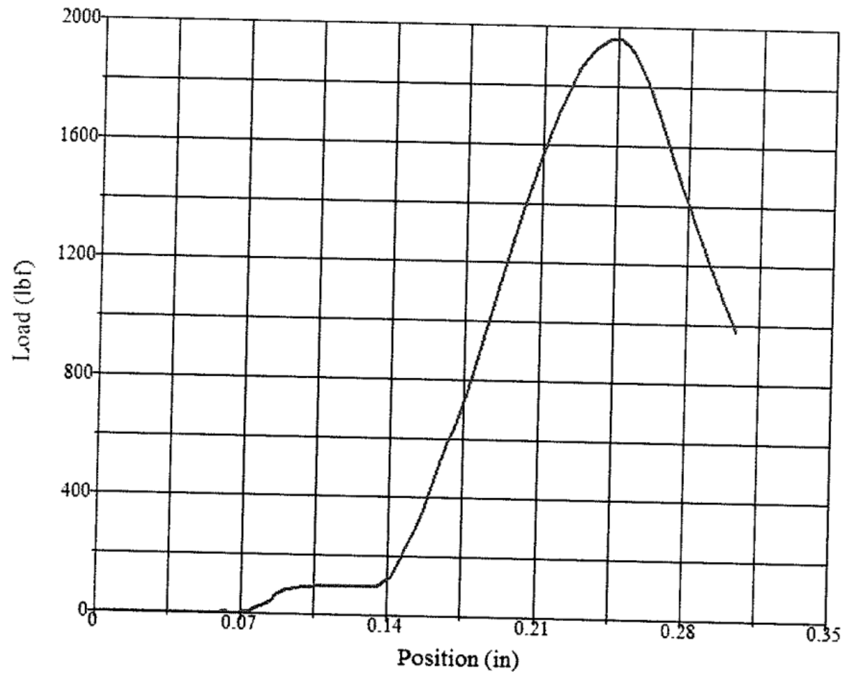
Counter:	147
Elapsed Time:	00:00:08
Specimen Identification:	5-1
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:47:31 AM
End Date:	2/16/2009
End Time:	10:47:39 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	1865 lbf

CEINSTRON1148

10:49:32 AM 2/16/2009

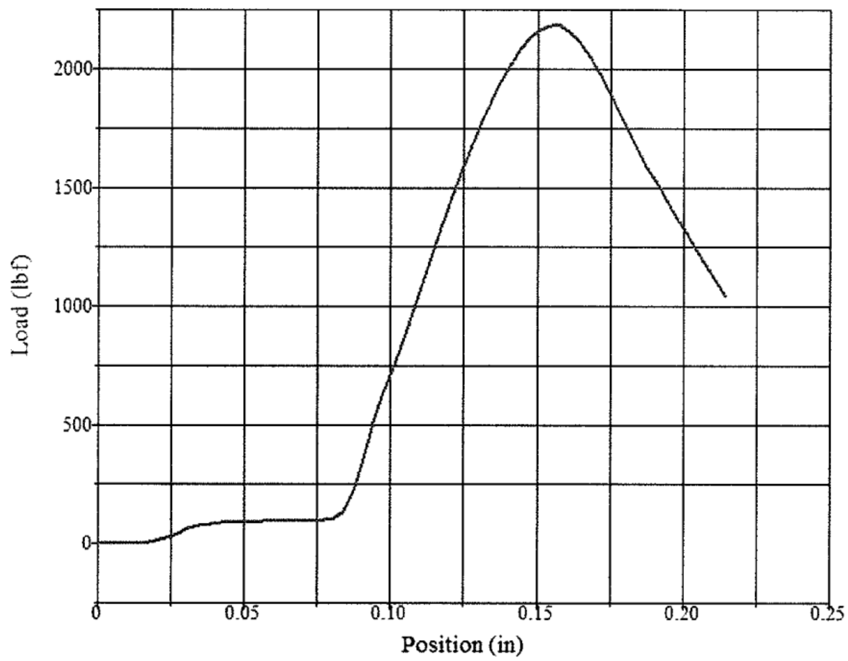


Test Summary

Counter:	148
Elapsed Time:	00:00:09
Specimen Identification:	5-2
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:49:17 AM
End Date:	2/16/2009
End Time:	10:49:26 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	4.0000 in
Area:	12.5664 in^2
Peak Load:	1961 lbf



Test Summary	
Counter:	149
Elapsed Time:	00:00:06
Specimen Identification:	5-3
Material:	Pavement
Comments:	
Procedure Name:	ITS
Start Date:	2/16/2009
Start Time:	10:51:02 AM
End Date:	2/16/2009
End Time:	10:51:08 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results	
Diameter:	4.0000 in
Area:	12.5664 in²
Peak Load:	2184 lbf

Appendix 3: Volumetric Mix Design Data

Sample ID	Sample #	Compaction Temperature (°C)	Air Voids (%)	BSG
RAP + 1% VB	1	122.0	10.50	2.224
	2	124.5	9.34	2.253
	3	119.5	7.93	2.288
	4	120.0	8.33	2.278
RAP + 1% VB + 2.0% Sasobit®	5	118.5	6.56	2.322
	6	124.0	7.53	2.298
	7	120.5	8.57	2.272
	8	119.5	7.24	2.305
RAP + 1% VB + 0.4% zeolite	9	120.5	6.60	2.321
	10	123.0	5.88	2.339
	11	122.5	6.40	2.326
	12	123.5	6.72	2.318

Appendix 4: Contact Angle ANOVA

Calculated F values in red indicate significance. Critical F values were taken from Appendix 6: Critical Values of the F Distribution on pages 908 to 910 of Applied Statistics for Engineers and Scientists (Petruccelli, Nandram, Chen).

Aged Binder + 1.0% Virgin Binder (VB)						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	15	145.337	9.689	0.283	2.494	3.574
Error	72	2468.506	34.285			
Total	87	2613.843				

VB only						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	26	144.315	5.551	0.533	2.372	3.319
Error	148	1541.595	10.416			
Total	174	1685.909				

Aged + 1.0% VB to 100% VB						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	15	471.726	31.448	0.953	3.222	5.160
Error	27	891.072	33.003			
Total	42	1362.798				

Sasobit Aged + 1.0% VB vs VB						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	17	895.283	52.664	5.908	3.154	4.990
Error	42	374.379	8.914			
Total	59	1269.662				

0.2% zeolite Aged + 1.0% VB vs VB						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	15	246.734	16.449	1.570	3.142	4.961
Error	51	534.247	10.475			
Total	66	780.982				

0.4% zeolite Aged + 1.0% VB vs VB						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	37	874.124	23.625	0.580	3.107	4.877
Error	55	2240.619	40.739			
Total	92	3114.743				

All Slides						
Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	15	4454.021	296.9347	47.463	1.938	2.511
Error	247	1545.260	6.2561116			
Total	262	5999.280				

1.0% VB + 0.4% zeolite vs 100% VB					
Source	Df	SS	MS	Fcalc	Fcritical (95)
Treatment	26	13.273	0.510484359	0.022	3.15
Error	55	1263.648	22.97540961		
Total	81	1276.920			

1.0% VB +AB+ 2.0% Sasobit® vs 100% AB					
Source	Df	SS	MS	Fcalc	Fcritical (95)
Treatment	15	258.440	17.22933442	0.956	3.257
Error	18	324.421	18.02340187		
Total	33	582.861			

1.0% VB + 2.0% Sasobit® vs 100% VB					
Source	Df	SS	MS	Fcalc	Fcritical (95)
Treatment	26	1.729	0.06649484	0.008	1.729
Error	42	333.290	7.93548249		
Total	68	335.019			

1.0VB +AB+ 2.0% Sasobit® vs 100% AB					
Source	Df	SS	MS	Fcalc	Fcritical (95)
Treatment	15	891.187	59.41245	3.154	3.093
Error	38	715.894	18.83933		
Total	53	1607.081			

Appendix 5: Dynamic Modulus Raw Data

Control Mix

		Sample 1				Sample 2				Sample 3			
		Unconditioned		Conditioned		Unconditioned		Conditioned		Unconditioned		Conditioned	
Temp (C)	Freq (Hz)	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle
-10	10	2.63.E+06	6.8312	3.48E+06	5.8965	4.45E+06	5.9444	2.79E+06	6.9319	2.85E+06	6.7711	3.14E+06	9.6598
	5	2.96.E+06	6.5884	5.23E+06	6.0378	8.74E+06	5.2766	4.02E+06	14.7771	4.09E+06	5.1605	3.01E+06	9.1958
	1	2.75.E+06	7.4542	4.13E+06	8.8758	3.99E+06	6.0861	3.04E+06	5.0986	2.60E+06	6.4617	2.66E+06	10.3311
	0.1	1.93.E+06	9.3339	2.82E+06	8.8875	3.26E+06	9.0564	2.06E+06	8.453	2.16E+06	7.9055	1.96E+06	13.505
4.4	10	1.85.E+06	11.6112	1.82E+06	12.5821	2.35E+06	11.2084	1.33E+06	11.496	1.89E+06	11.6628	1.87E+06	12.3688
	5	1.71.E+06	11.4802	1.66E+06	12.6068	2.22E+06	11.4742	1.25E+06	10.8384	1.77E+06	11.4303	1.76E+06	11.8378
	1	1.45.E+06	13.0746	1.38E+06	14.2708	1.82E+06	12.16	1.03E+06	13.0244	1.44E+06	12.6349	1.45E+06	13.2365
	0.1	9.80.E+05	17.2996	8.84E+05	18.693	1.30E+06	16.466	7.28E+05	17.0771	1.04E+06	16.5517	9.74E+05	17.6155
21.1	10	8.33.E+05	21.5871	1.25E+05	28.6031	1.28E+06	18.3487	4.52E+05	23.0370	8.72E+05	20.5212	8.50E+05	21.54
	5	7.17.E+05	21.7000	1.01E+05	26.5122	1.14E+06	18.5013	3.86E+05	24.7606	7.63E+05	21.0339	7.35E+05	21.5191
	1	4.78.E+05	25.3374	6.88E+04	21.6562	7.88E+05	22.0847	2.49E+05	27.0191	5.19E+05	24.241	4.96E+05	24.712
	0.1	2.46.E+05	31.6493	4.43E+04	17.9913	4.28E+05	28.0072	1.33E+05	28.1934	2.69E+05	30.6413	2.59E+05	30.3174
37.8	10	2.90.E+05	30.3074	1.83E+05	33.3695	3.31E+05	30.797	2.57E+05	29.1159	3.09E+05	30.7674	2.56E+05	31.5569
	5	2.30.E+05	30.2398	1.41E+05	33.2351	2.64E+05	30.4841	2.07E+05	28.4629	2.45E+05	30.8274	2.01E+05	31.0021
	1	1.37.E+05	30.4976	7.62E+04	31.6527	1.58E+05	28.1764	1.23E+05	28.1367	1.41E+05	31.6264	1.16E+05	30.6526
	0.1	6.68.E+04	28.7410	3.61E+04	26.3444	7.53E+04	28.3711	6.45E+04	25.1213	6.79E+04	29.7563	5.73E+04	27.7194

Control Mix + 2.0% Sasobit®

		Sample 5				Sample 6				Sample 7			
		Unconditioned		Conditioned		Unconditioned		Conditioned		Unconditioned		Conditioned	
Temp (C)	Freq (Hz)	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle
-10	10	3.12E+06	5.6959	3.95E+06	6.3169	2.55E+06	5.1167	9.01E+05	7.4485	4.58E+06	6.7085	3.61E+06	6.8085
	5	4.44E+06	5.6578	5.49E+06	10.8308	2.98E+06	4.6987	1.02E+06	4.6678	4.42E+06	5.8766	3.51E+06	6.9056
	1	4.58E+06	5.5184	3.54E+06	6.4588	2.38E+06	5.3506	1.04E+06	6.1971	3.99E+06	4.5876	3.51E+06	7.2492
	0.1	3.44E+06	5.9588	3.11E+06	7.9551	2.17E+06	6.2677	8.78E+05	7.8454	3.38E+06	6.7078	2.74E+06	9.3235
4.4	10	2.11E+06	9.3260	2.01E+06	10.9833	1.78E+06	7.9400	1.69E+06	9.9419	2.98E+06	8.0918	2.91E+06	8.8362
	5	2.09E+06	9.0645	1.92E+06	10.4518	2.17E+06	7.4021	1.72E+06	7.8688	2.76E+06	9.1588	2.91E+06	8.8362
	1	2.93E+06	9.6562	2.33E+06	10.5753	2.08E+06	8.2468	1.47E+06	8.9254	2.54E+06	10.3983	1.90E+06	10.3309
	0.1	1.39E+06	12.4741	1.21E+06	14.1479	1.22E+06	10.6458	1.02E+06	12.3552	1.83E+06	12.3328	1.44E+06	12.7142
21.1	10	1.20E+06	15.5064	2.91E+05	17.3004	1.07E+06	13.7493	8.58E+05	17.0841	1.51E+06	13.981	1.18E+06	16.255
	5	1.10E+06	15.4248	2.83E+05	19.4226	9.77E+05	13.8604	7.69E+05	16.4020	1.33E+06	15.4944	1.06E+06	16.8037
	1	8.62E+05	15.3736	2.95E+05	17.4046	7.82E+05	15.8455	5.85E+05	19.1455	1.06E+06	16.7197	9.13E+05	19.1141
	0.1	5.43E+05	22.2312	1.35E+05	24.6506	4.88E+05	20.8586	3.59E+05	23.4097	6.09E+05	22.578	4.96E+05	24.3327
37.8	10	5.36E+05	25.7665	4.63E+05	27.025	4.55E+05	24.6746	3.34E+05	27.0217	6.59E+05	25.3501	5.11E+05	24.7914
	5	4.51E+05	25.5717	3.87E+05	26.5668	3.91E+05	24.6149	2.76E+05	27.3853	5.54E+05	25.1052	4.34E+05	25.5256
	1	2.86E+05	29.1314	2.41E+05	29.4223	2.56E+05	27.2178	1.73E+05	28.7909	3.57E+05	27.2107	2.71E+05	28.6572
	0.1	1.48E+05	32.0784	1.19E+05	32.4114	1.38E+05	30.7378	8.82E+04	31.6115	1.82E+05	31.6525	1.35E+05	31.9416

Control Mix + 0.4% zeolite

		Sample 9				Sample 10				Sample 11			
		Unconditioned		Conditioned		Unconditioned		Conditioned		Unconditioned		Conditioned	
Temp (C)	Freq (Hz)	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle
-10	10	8.32E+05	7.2608	3.61E+06	8.8047	2.60E+06	6.6045	2.94E+06	8.0553	2.64E+06	6.1157	4.04E+06	8.5302
	5	8.47E+05	5.3434	3.76E+06	8.5312	2.53E+06	5.0690	2.46E+06	6.8622	3.05E+06	5.1223	4.62E+06	8.0766
	1	7.65E+05	5.2998	3.17E+06	10.1742	2.61E+06	5.0924	2.51E+06	9.4681	2.55E+06	5.9518	3.96E+06	8.5675
	0.1	7.40E+05	9.2278	2.40E+06	12.4683	2.26E+06	6.6698	2.17E+06	13.038	2.24E+06	7.0689	2.88E+06	10.7054
4.4	10	1.93E+06	10.1204	1.25E+06	15.1319	4.44E+05	9.8488	2.63E+05	12.9963	1.78E+06	9.6565	1.41E+06	14.2167
	5	1.83E+06	10.5803	1.15E+06	14.9007	4.31E+05	9.4318	2.44E+05	13.0396	1.67E+06	10.0081	1.31E+06	14.0141
	1	1.53E+06	11.4111	8.88E+05	16.3842	3.65E+05	10.2533	1.95E+05	14.2115	1.56E+06	10.71	1.03E+06	15.3573
	0.1	1.10E+06	15.7416	5.93E+05	20.8590	2.67E+05	14.2632	1.36E+05	18.7911	1.08E+06	14.502	7.13E+05	19.2017
21.1	10	9.32E+05	20.0316	6.08E+05	23.1669	9.69E+05	17.7073	6.73E+05	22.0254	1.01E+06	18.1006	6.63E+05	22.1585
	5	8.14E+05	20.6751	5.24E+05	23.1159	8.63E+05	18.3563	5.86E+05	22.8705	8.84E+05	19.1862	5.74E+05	22.2394
	1	5.64E+05	24.1629	3.45E+05	26.0796	6.17E+05	22.6384	3.92E+05	25.7255	6.34E+05	22.0970	3.86E+05	24.9694
	0.1	3.00E+05	30.3228	1.85E+05	29.6898	3.44E+05	28.8743	2.08E+05	30.8243	3.47E+05	28.8311	2.04E+05	29.4356
37.8	10	3.49E+05	31.5080	2.11E+05	30.3691	3.41E+05	29.1859	2.15E+05	30.4651	3.29E+05	30.5067	2.06E+05	30.4546
	5	2.79E+05	30.7807	1.67E+05	29.6531	2.73E+05	29.7347	1.72E+05	29.3685	2.63E+05	30.277	1.61E+05	29.8772
	1	1.62E+05	32.0073	9.94E+04	28.8821	1.59E+05	31.1873	1.01E+05	28.9912	1.53E+05	30.991	9.60E+04	28.3297
	0.1	8.65E+04	30.1928	5.27E+04	25.4490	7.69E+04	29.6401	5.23E+04	26.218	7.50E+04	28.5104	5.13E+04	24.9499

Appendix 6: |E*| ANOVA Tables

All ANOVA were calculated for 37.8°C.

Control:10Hz Frequency

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	9063706667	4531853333	3.038	**2.996**	4.605
Error	3	4475329333	1491776444			
Total	5	13539036000				

Control: 5 Hz Frequency

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	5986936817	2993468408	2.801	**2.996**	4.605
Error	3	3206503933	1068834644			
Total	5	9193440750				

Control: 1 Hz Frequency

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	2421126288	1210563144	2.380	**2.996**	4.605
Error	3	1525881893	508627297.6			
Total	5	3947008181				

Control: 0.1Hz Frequency

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	451551100.2	225775550.1	1.420	**2.996**	4.605
Error	3	476915590.7	158971863.6			
Total	5	928466690.8				

2.0% Sasobit: 10Hz Frequency

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	19557892267	9778946133	0.778	**2.996**	4.605
Error	3	37694028267	12564676089			
Total	5	57251920533				

2.0% Sasobit®: 5 Hz Freq

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	14787756150	7393878075	0.829	**2.996**	4.605
Error	3	26749559933	8916519978			
Total	5	41537316083				

2.0% Sasobit: 1Hz Freq, Temp 37.8C

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	7611994017	3805997008	1.101	2.996	4.605
Error	3	10366851867	3455617289			
Total	5	17978845883				

2.0% Sasobit: 0.1Hz Freq

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	2640291083	1320145541	1.813	2.996	4.605
Error	3	2184691131	728230376.9			
Total	5	4824982213				

0.4% Zeolite: 10Hz

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	24992469600	12496234800	144.550	2.996	4.605
Error	3	259347733.3	86449244.44			
Total	5	25251817333				

0.4% Zeolite: 5Hz

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	16682717400	8341358700	126.270	2.996	4.605
Error	3	198178600	66059533.33			
Total	5	16880896000				

0.4% Zeolite: 1Hz

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	5298006211	2649003105	145.593	2.996	4.605
Error	3	54583839.33	18194613.11			
Total	5	5352590050				

0.4% Zeolite: 0.1Hz

Source	Df	SS	MS	Fcalc	Fcritical (95)	Fcritical (99)
Treatment	2	1127784600	563892300	22.113	2.996	4.605
Error	3	76502015.33	25500671.78			
Total	5	1204286615				